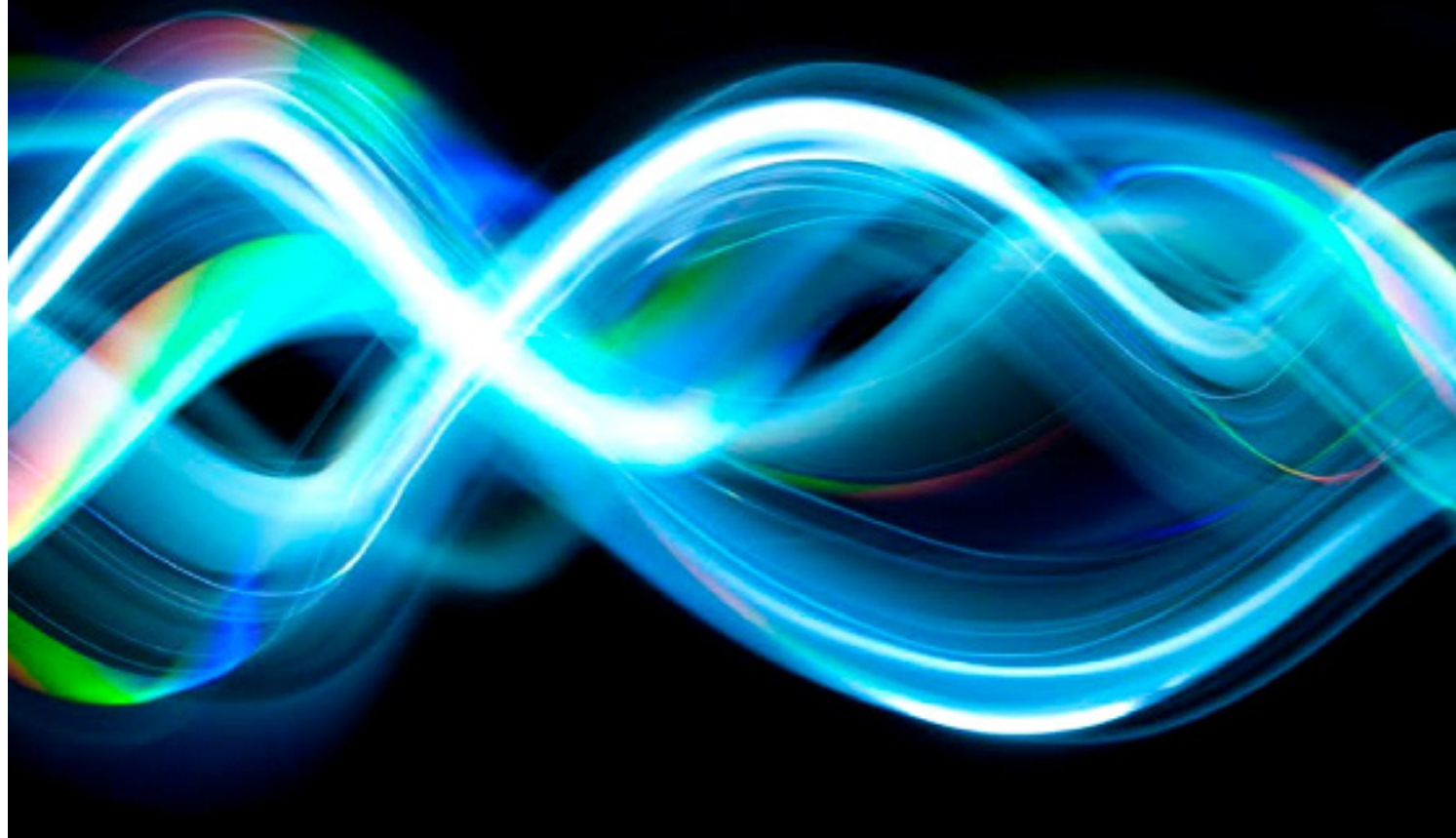


IEEE Std 3003.1™-2019

Recommended Practice
for System Grounding of
Industrial and Commercial
Power Systems



IEEE Recommended Practice for System Grounding of Industrial and Commercial Power Systems

Developed by the

Industrial and Commercial Power Systems Standards Development Committee
of the
IEEE Industry Applications Society

Approved 13 June 2019

IEEE SA Standards Board

Abstract: Discussed in this recommended practice is the system grounding of industrial and commercial power systems. The recommended practices in this document are intended to provide explanations of how electrical systems operate. It can also be an aid to all engineers responsible for the electrical design of industrial and commercial power systems.

Keywords: effectively grounded, ground, grounding system, high resistance ground, IEEE 3003.1™, neutral

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PDF: ISBN 978-1-5044-5944-0 STD23745
Print: ISBN 978-1-5044-5945-7 STDPD23745

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Introduction

This introduction is not part of 3003.1–2019, IEEE Recommended Practice for System Grounding of Industrial and Commercial Power systems.

IEEE 3000 Series®

This recommended practice was developed by the Industrial and Commercial Power Systems Standards Development Committee of the IEEE Industry Applications Society as part of a project to repackage IEEE's popular series of "color books." The goal of this project is to speed up the revision process, eliminate duplicate material, and facilitate use of modern publishing and distribution technologies.

When this project is completed, the technical material included in the 13 "color books" will be included in a series of new standards. Approximately 60 "dot" standards, organized into the following categories, will provide in-depth treatment of many of the topics formerly covered in the color books:

- Power Systems Design (3001 series)
- Power Systems Analysis (3002 series)
- Power Systems Grounding and Bonding (3003 series)
- Protection and Coordination (3004 series)
- Emergency, Stand-By Power, and Energy Management Systems (3005 series)
- Power Systems Reliability (3006 series)
- Power Systems Maintenance, Operations, and Safety (3007 series)

In many cases, the material in a "dot" standard comes from a particular chapter of a particular color book. In other cases, material from several color books has been combined into a new "dot" standard. The material in this recommended practice largely comes from Chapter 1 of IEEE Std 142™-2007.

IEEE Std 3003.1™

This recommended practice covers the system grounding of industrial and commercial power systems. It is likely to be of greatest value to the power-oriented engineer with limited experience in this area. It can also be an aid to all engineers responsible for the electrical design of industrial and commercial power systems.

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IEEE Recommended Practice for System Grounding of Industrial and Commercial Power Systems

1. Overview

1.1 Scope

This recommended practice covers the system grounding of industrial and commercial power systems. The basic reasons for grounding or not grounding the electrical system and the various types of system grounding, as well as the practices commonly used to ground electrical systems are discussed.

1.2 Purpose

Grounding of an electrical system is a decision that must be faced by engineers charged with planning or modifying electrical distribution. Grounding in some form is generally recommended, although there are certain exceptions. Several methods and criteria exist for system grounding; each has its own purpose.

It is the intention of this recommended practice to assist the engineer in making decisions by presenting basic reasons for grounding or not grounding and by reviewing general practices and methods of system grounding. The practices set forth herein are primarily applicable to industrial, institutional, and/or commercial power systems that distribute and utilize power at medium or low voltage, usually within a smaller geographical area than is covered by a utility.

Where distances or power levels may dictate circuitry and equipment similar to a utility, consideration of utility practices is warranted. In addition to the general technical considerations in the practice of grounding as discussed in this recommended practice, pertinent codes or standards imposed by local regulatory authorities, the particular needs of service, and the experience and training of the workforce should also be considered. Where an industrial or commercial power system includes power-generating equipment, the reasons for grounding these components may be the same as those for grounding similar components of public utility systems. The methods of grounding would generally be similar under like conditions of service. However, in the industrial or commercial setting, conditions of service may be altered by the following:

- a) Location within the power system
- b) Individual generator characteristics
- c) Manufacturing process requirements
- d) Emergency/life safety requirements of the local codes

The standards listed in [Clause 2](#) are considered minimum requirements for the protection of life and property and should be carefully reviewed during the course of system design. The recommended practices in this document are intended to supplement, and not negate, any of the requirements in the NEC, IEC, or any other location-specific regulatory codes.

The recommended practices in this document are intended to provide explanations of how electrical systems operate. A better understanding of the electrical principles will assist the engineer in implementing the recommendations in a manner that best provides for the needs of a specific design function.

1.3 Covered—system grounding

System grounding is the intentional connection to ground of a phase or neutral conductor for the purpose of:

- a) Controlling the voltage with respect to earth, or ground, within predictable limits, and
- b) Providing for a flow of current that will allow detection of an unwanted connection between system conductors and ground. Such detection may then initiate operation of automatic devices to remove the source of voltage from these conductors.

The control of voltage to ground limits the voltage stress on the insulation of conductors so that insulation performance can more readily be predicted. The control of voltage also allows reduction of shock hazard to persons who might come in contact with live conductors.

1.4 Not covered—equipment grounding and bonding

The terms grounded and bonded are defined in the CEC, IEC, NESC, and NEC. “Bonding” is the electrical interconnecting of non-current carrying conductive parts designed to achieve a low impedance conductive path. This definition is self-explanatory and implies that the conductive path should be adequately sized, and connections properly installed, in order to maintain a path with impedance as low as possible. The term bonding obviously is not exclusive to grounded systems. “Grounded” means connected to, or in contact with, the earth, or connected to some extended conductive body that serves in place of the earth, whether the connection is intentional or accidental. The earth or the other conductive body is known as the “ground” in North America and areas of the world that use the CEC or NEC, and “earth” in the areas of the world that use the IEC. When used as a verb, “grounding” is the act of establishing the aforementioned connection to ground or the conductive body. When used as an adjective, grounding describes the conductor or metal part that is used to make the connection to ground.

Equipment grounding and bonding is covered in IEEE Std 3003.2™, IEEE Recommended Practice for Equipment Grounding and Bonding in Industrial and Commercial Power Systems.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEC 60364-1, Electrical Installations of Buildings.

IEEE Std C37.101™, IEEE Guide for Generator Ground Protection.

IEEE Std 367™, IEEE Recommended Practice for Determining the Electric Power Station Ground Potential Rise and Induced Voltage from a Power Fault.

IEEE Std 3003.2™, IEEE Recommended Practice for Equipment Grounding and Bonding in Industrial and Commercial Power Systems.

3. Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.¹

3.1 Grounding terminology as used worldwide

earth: *See:* **ground.**

earthed: *See:* **grounded.**

effectively grounded: Grounded through a sufficiently low impedance (inherent or intentionally added, or both) such that for all system conditions the ratio of zero-sequence reactance to positive-sequence reactance (X_0/X_1) is positive and less than or equal to 3, and the ratio of zero-sequence resistance to positive-sequence reactance (R_0/X_1) is positive and less than 1.

equipment grounding conductor (EGC): *See:* **protective conductor.**

exposed-conductive-parts (ECP): A conductive part, forming part of electrical equipment, which can be touched (even if out of reach) and not live, but likely to become live when basic insulation fails. ECPs are required to be connected to the same earthing system individually, in groups or collectively, via a protective conductor.

extraneous-conductive-part (EXCP): A conductive part, not forming part of the electrical installation, and liable to introduce an electric potential, generally the electric potential of a local earth/ground.

ground: A conducting connection, whether intentional or accidental, between an electrical circuit or equipment and the earth, or to some other body that serves in place of the earth. This term is considered equivalent to the term “earth”.

ground (earth) electrode: Conductive part, which may be embedded in a specific conductive medium (e.g., concrete or coke) in electric contact with the earth.

grounded: Connected to earth or to an extended conducting body that serves instead of the earth, whether the connection is intentional or accidental.

grounded system: A system in which at least one conductor or point (usually the middle wire or neutral point of transformer or generator windings) is intentionally grounded, either solidly or through an impedance.

grounding system: A system that consists of all interconnected grounding connections in a specific power system and is defined by its isolation from adjacent grounding systems. The isolation is provided by transformer primary and secondary windings that are coupled only by magnetic means.

high-resistance grounded: A resistance grounded system designed to limit ground-fault current to a value that can be allowed to flow for an extended period of time, while still meeting the criteria of $R_0 < X_{C0}$, so that transient voltages from arcing ground faults are reduced. The ground-fault current is usually limited to less than 10 A, resulting in limited damage even during prolonged faults.

¹*IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>.

local ground (local earth): Part of the ground (earth) which is in electric contact with a ground (earth) electrode, whose electric potential is not necessarily equal to zero.

low-resistance grounded: A resistance grounded system that permits a higher ground-fault current to flow to obtain sufficient current for selective relay operation. Usually meets the criteria of R_0/X_0 less than or equal to 2. Ground-fault current is typically between 100 A and 1000 A.

neutral point: Common point of a star-connected polyphase system or earthed mid-point of a single-phase system.

neutral conductor: The conductor connected to the neutral point of a system that is intended to carry current under normal conditions.

per-phase charging current (ICO): The current (V_{LN}/X_{C0}) that passes through one phase of the system to charge the distributed capacitance per phase-to-ground of the system.

protective conductor: The conductor provided for protective functions, such as providing a path for fault current to flow back to the source, for connecting exposed-conductive-part ECPs, such as non-current carrying metal parts of equipment, raceways, and other enclosures to earth, etc. There are often specific names for this conductor, such as “equipment grounding conductor (EGC)” in the NEC, “protective earth conductor (PE)” in the IEC, and “bonding conductor (BC)” in the CEC.

protective earth neutral (PEN): A conductor that combines the functions of the protective conductor and the neutral conductor, used in some IEC grounding systems.

R_0 : The per phase zero sequence resistance of the system.

reactance grounded: Grounded through an impedance, the principal element of which is inductive reactance.

remote (or reference) ground (earth): Part of the ground (earth) considered as conductive, whose electric potential is conventionally taken as zero, being outside the zone of influence of any earthing arrangement.

resistance grounded: Grounded through an impedance, the principal element of which is resistance.

resonant grounded: A system in which the capacitive charging current is neutralized by an inductive current produced from a reactor connected between the system neutral and ground. By properly “tuning” the reactor (selecting the right tap), a low magnitude of fault current can be achieved. In general, when this occurs the arc will not maintain itself and the ground fault is extinguished or “quenched” by the parallel circuit consisting of inductance (L) and capacitance (C). This happens when,

$$\omega L = \frac{1}{\omega C} \text{ or } f = \frac{1}{2\pi\sqrt{LC}}$$

R_G : Value of the resistance-to-earth of an electrode that grounds a point of the electrical source of a system (e.g., the neutral point of a transformer). It is not a resistance intentionally inserted. *See also: solidly grounded.*

R_N : Value of the resistance-to-earth of a neutral grounding resistor.

separately derived system: A wiring system whose power is derived from a generator, transformer, or converter windings and has no direct electrical connection, including a solidly connected grounded circuit conductor, to supply conductors originating in another system.

solidly grounded: System in which at least one neutral point is grounded (earthed) directly, with no intentional device having a resistance/impedance designed to limit the line-to-ground short-circuit current.

static charge: The electricity generated when two dissimilar substances come into contact. Conveyor belts are active producers of static electricity.

switching surge: A transient wave of overvoltage in an electric circuit caused by the operation of a switching device interrupting current.

system charging current: The total distributed capacitive charging current ($3 V_{LN}/X_{C0}$) of a three-phase system.

three-phase, four-wire system: A system of alternating current supply comprising four conductors, three of which are connected as in a three-phase three-wire system, the fourth being connected to the neutral point of the supply or midpoint of one phase in case of delta-connected transformer secondary for the purpose of conducting load current.

three-phase, three-wire system: A system of alternating current supply comprising three conductors, between successive pairs of which are maintained alternating differences of potential successively displaced in phase by one third of a period.

touch voltage: The difference in potential between metallic objects or structures within the substation site that may be bridged by direct hand-to-hand or hand-to-feet contact.

transient overvoltage: The temporary overvoltage associated with the operation of a switching device, a fault, a lightning stroke, an arcing ground fault on an ungrounded system, or other instigating events.

ungrounded system: A system without an intentional connection to ground except through potential indicating or measuring devices or other very high-impedance devices.

V_{LN} : The line-to-neutral voltage.

X_{C0} : The distributed per-phase capacitive reactance to ground of the system.

X_0 : Zero-sequence reactance of the system.

X_1 : Positive-sequence reactance of the system.

X_2 : Negative-sequence reactance of the system.

3.2 IEC system grounding terminology

Rather than using dual terminology throughout this recommended practice, basic system grounding nomenclature from the International Electrotechnical Commission (IEC) as found in IEC 60364-1, is provided in this section for relation to the concepts presented in the remainder of this document.

When discussing what in North America is called grounding, of primary importance is the understanding that the term for ground in much of the world is earth (E). Translated to French, earth is terre (T) and for system definitions equates to a solidly grounded system. Systems without a direct connection to earth (ungrounded) or connected through a sufficiently high impedance are called isolated (I). T or I may be used in the first of two positions of an IEC system grounding configuration to indicate source grounding. T may also be found in the second position indicating a direct connection to earth at the device being supplied. Neutral (N) in the second position indicates connection to ground via the supply network.

3.2.1 TT systems

TT (Terre-Terre) systems are defined as the electrical systems whose devices being supplied are connected to ground electrodes electrically independent of the ground electrodes of the source (e.g., the local utility) [Figure 1](#).

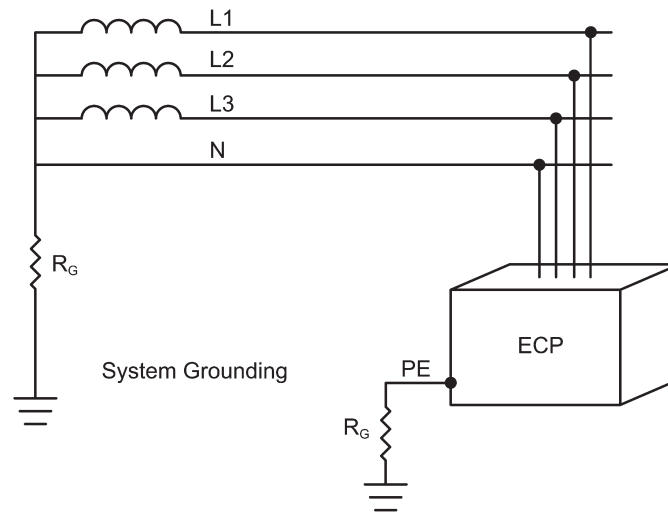


Figure 1—TT system

This is the grounding method adopted for low-voltage systems (i.e., not exceeding 1 kV) supplying dwelling units in several countries, to list a few: Algeria, Belgium, Denmark, Egypt, France, Greece, Italy, Japan, Kenya, Luxemburg, Morocco, Tunisia, Spain, Portugal, Turkey, United Arab Emirates, etc.

3.2.2 TN system

TN (Terre-Neutral) systems are defined as the electrical systems whose ECPs are directly connected by a protective conductor to the solidly grounded point of the source (e.g., the neutral point [Figure 2](#). Of note; connection of the PE to individual ECPs may intentionally or unintentionally provide additional connections to earth throughout the system. The different arrangements of neutral and protective conductors determine three types of TN system. In TN-S systems [Figure 2](#), also as in typical industrial and commercial applications, two separate wires are used as protective and neutral conductors, throughout the system.

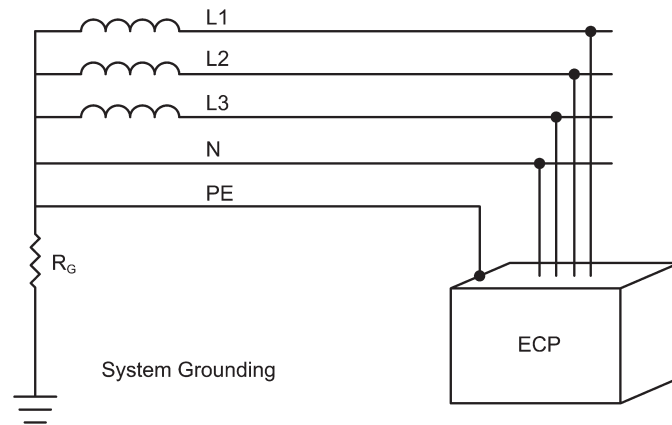


Figure 2—TN-S system

In TN-C systems, the functions of the neutral conductor and of the PE are combined in the PEN conductor throughout the system [Figure 3](#). This is a configuration typical of utilities in North America, but not a recommended practice for industrial and commercial power systems.

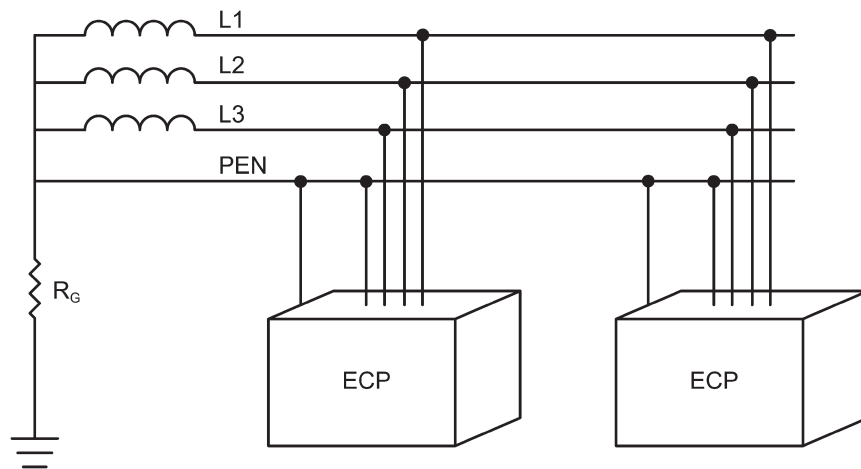


Figure 3—TN-C system

In TN-C-S systems, the functions of the neutral conductor and of the PE are combined in a single conductor in a part of the system. Such conductor is referred to as protective earthed neutral (PEN). When the earthing point is provided to low-voltage users by a utility network, the TN-C-S system is also referred to as protective multiple earthing (PME) as shown in [Figure 4](#). In North America, the transition point from PEN to PE is typical of the utility to user interface with inclusion of an electrode for an intentional connection to earth at the service entrance.

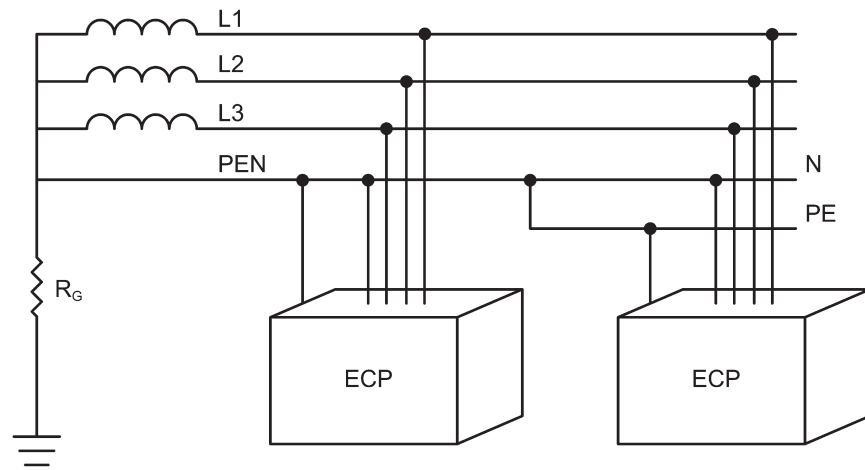


Figure 4—TN-C-S system

3.2.3 IT system

Isolation terre (IT) systems are defined as the electrical systems whose source is insulated from ground or connected to it through sufficiently high impedance. In this arrangement it is advisable, although not prohibited, to omit the neutral wires to loads in order to safeguard its isolation from ground.

In the event of a first fault between a line conductor and an ECP, or earth, fault currents can still flow due the distributed capacitance to ground of the electrical system. Such currents are relatively low in intensity, but may be sufficient to cause harmful touch voltages. Thus, in order to limit such hazard, ECPs are required to be earthed individually, in groups, or collectively as shown in [Figure 5](#) and [Figure 6](#).

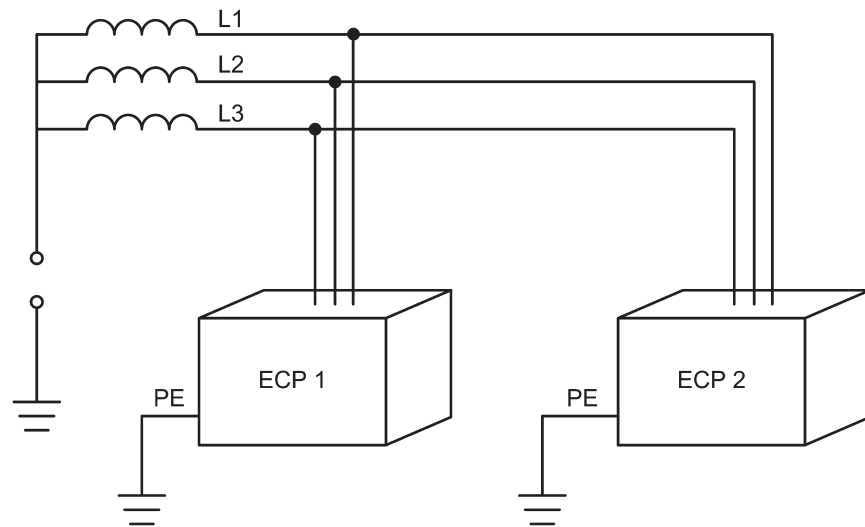


Figure 5—ECPs earthed individually in IT systems

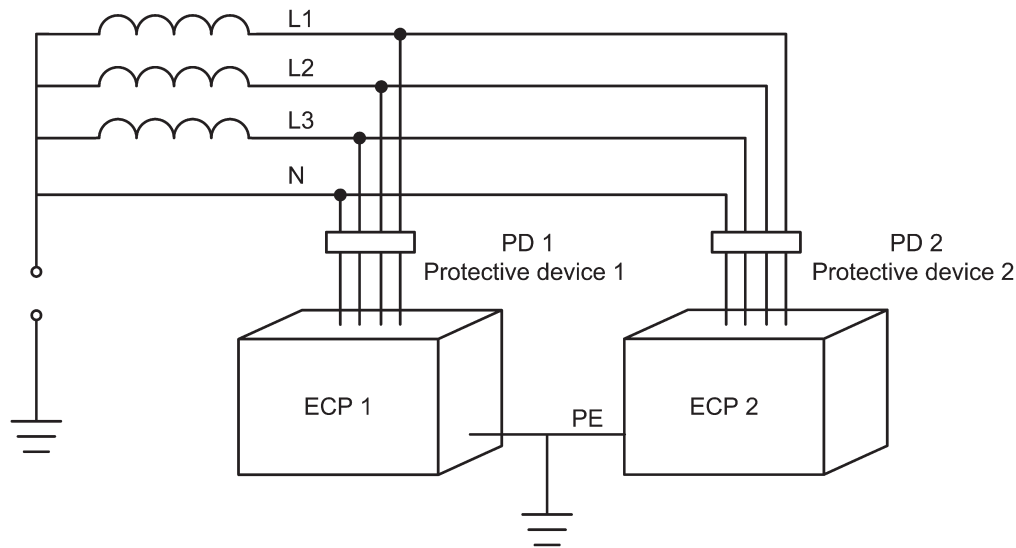


Figure 6—ECPs earthed collectively in IT systems

4. Methods of system neutral grounding

4.1 Introduction

Most electrical systems employ some method of grounding the system neutral at one or more points. Similar to the IEC T and I designations, these methods can be divided into two general categories: solid grounding and impedance grounding. Impedance grounding may be further divided into several subcategories: reactance grounding, resistance grounding, and ground-fault neutralizer grounding. [Figure 7](#) shows examples of these methods of grounding.

Each method, as named, refers to the nature of the external circuit from system neutral to ground rather than to the degree of grounding. In each case, the impedance of the generator or transformer whose neutral is grounded is in series with the external circuit. Thus a solidly grounded generator or transformer may or may not furnish effective grounding to the system, depending on the system source impedance. For additional clarity, see the definition of “effectively grounded.”

Many of the concepts involved in defining system grounding types and levels are best explained in terms of symmetrical components or equivalent circuits. The reader who is not familiar with these analytical methods is referred to a text on symmetrical components for power systems, several of which are listed in the bibliography.

Molded-case circuit-breaker interrupting capabilities can be affected by the method of grounding. If other than solidly grounded wye systems are used, the circuit breakers’ single-pole interrupting ratings should be evaluated for the application [\[B20\]](#).

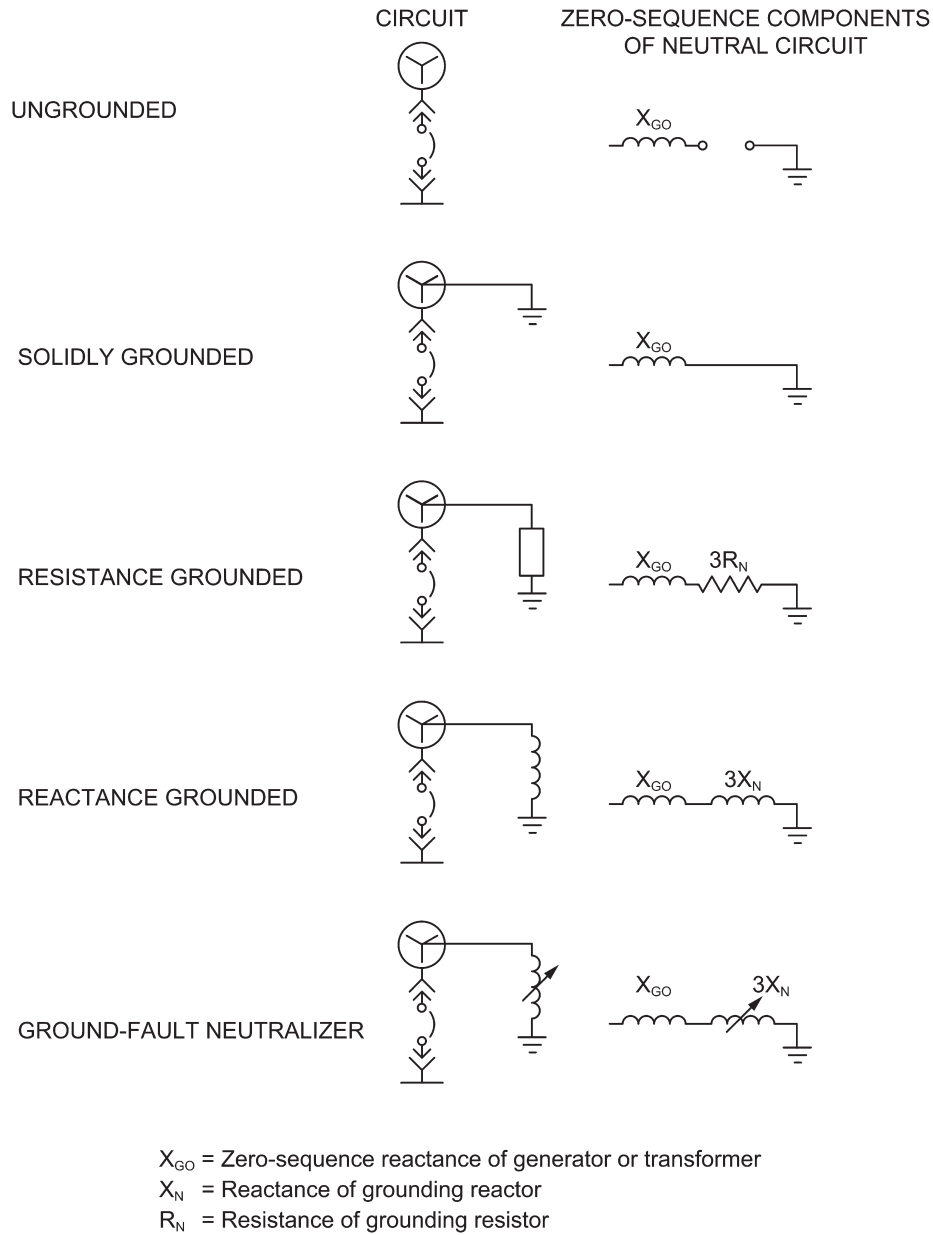


Figure 7—System neutral circuit and equivalent diagrams for ungrounded and grounded systems

4.2 Ungrounded system (no intentional grounding)

In an ungrounded system, there is no intentional connection between the system conductors and ground. However, as shown in Figure 8, there always exists a capacitive coupling between one system conductor and another, as well as between system conductors and ground. By virtue of the distributed capacitance from the system conductors to ground, the so-called ungrounded system is in reality a capacitance grounded system. Since the capacitance between phases has little effect on the grounding characteristics of the system, it will be disregarded. For simplicity, the distributed capacitive reactance to ground, X_{C0} , is assumed to be balanced.

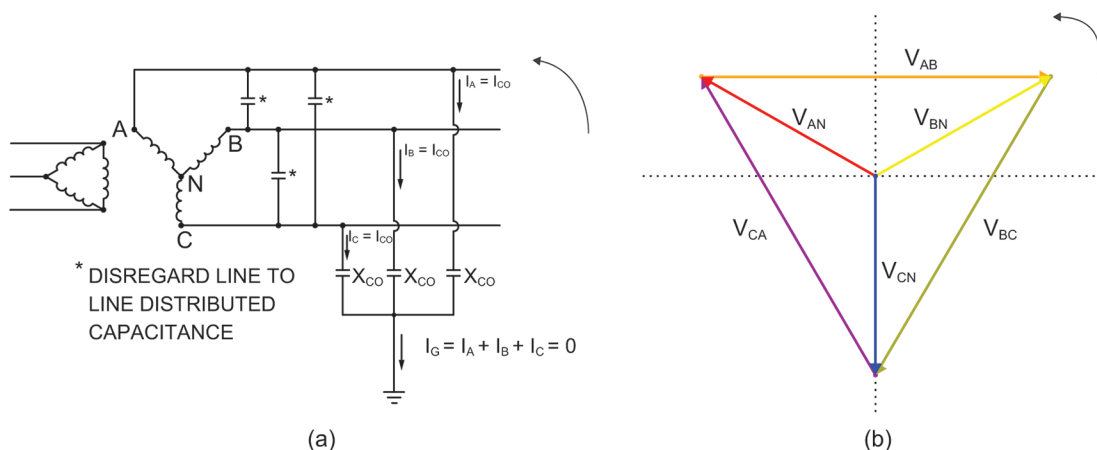


Figure 8—a) Ungrounded system circuit configuration, b) Voltage phasor diagram

In normal operating conditions, with balanced three-phase voltages applied to the lines, the capacitive charging current, I_{C0} , in each phase will be equal and displaced 120° from one another. The phase voltages to ground will also be equal and displaced 120° from one another. The phasor relationships can be determined. Since the neutral of the distributed capacitances is at earth potential, it follows that the neutral of the transformer is also at earth potential, being held there by the capacitance to ground.

If one of the system conductors, phase C for example, faults to ground, current flow through that capacitance to ground will cease, since no potential difference across it now exists. The voltage across the remaining two distributed capacitors to ground will increase from line-to-neutral to line-to-line. The capacitive charging current, I_{C0} , in the two phases without a fault will therefore increase by the square root of 3. As shown in Figure 9, the line-to-ground voltages are no longer 120° , but 60° apart. This causes the excessive terminal voltages during faults, along with the absence of a neutral conductor, precludes support of line-to-neutral loads on an ungrounded system.

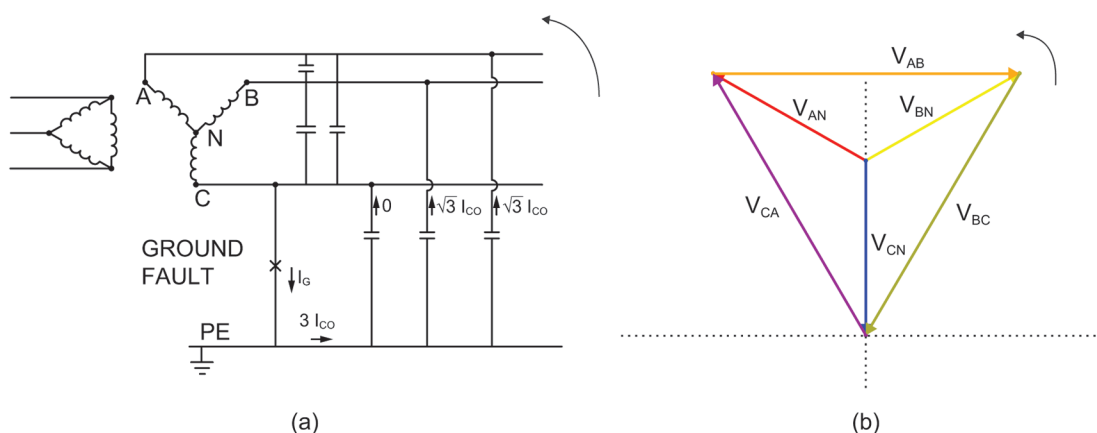


Figure 9—a) Single line-to-ground fault on an ungrounded system, b) Voltage phasor diagram

Hence, the vectorial sum of the capacitive charging current to ground is no longer zero, but is $3 I_{C0}$ or three times the original charging current per phase. The fault current, I_G , flowing from the faulted conductor to ground, leads the original line-to-neutral voltage ($V_{NC} = -V_{CN}$) by approximately 90° .

In an ungrounded system, it is possible for destructive transient overvoltages to occur throughout the system during restriking ground faults. These overvoltages, which can be several times normal in magnitude, result from a resonant condition being established between the inductive reactance of the system and the distributed capacitance to ground. Experience has proven that these overvoltages may cause failure of insulation at multiple locations in the system, particularly at motors. Transient overvoltages from restriking ground faults are the main reason why ungrounded systems are no longer recommended and grounded systems of some form are the predominant choice. To reduce transient overvoltages during restriking ground faults, one should ground the system using either solid or impedance grounding as indicated in [Figure 10](#).

Various detection schemes are used to detect the presence of a single line-to-ground fault. The simplest scheme employs three light bulbs rated for line-to-line voltage, each connected between line voltage and ground. Under normal operation, the three bulbs are illuminated with low equal intensity. When a single line-to-ground fault occurs, that bulb connected to the faulted phase is extinguished. The remaining two bulbs increase in intensity since the voltage on the phases without a fault increases from line-to-neutral to line-to-line. It should be noted that the light bulbs are a high resistance and to some extent provide a ground reference for the ungrounded system.

Another scheme frequently used takes the form of three voltage transformers with their primary windings connected in wye and the neutral point grounded. The secondary windings of the transformers are connected in broken delta, with a voltage relay connected in the open corner and used to operate an indication or alarm circuit. Using this scheme, loading resistors may be required either in the primary neutral or secondary circuit to avoid ferroresonance.

Locating a single line-to-ground fault on an ungrounded system can be time consuming. Usually, the first step is to open the secondary feeders, one at a time, to determine which feeder on which the fault is located. This is verified by observing the three lights to determine when the ground fault has been cleared. This process is repeated downstream until the faulted device is detected.

If a ground cannot be located before a second line-to-ground fault occurs on a different phase, a line-to-line fault will result. The current must be carried either by the protective conductor, metallic raceways, or by the earth. This will be contrasted later to a grounded system that develops enough fault current to clear, automatically and selectively, each faulted circuit.

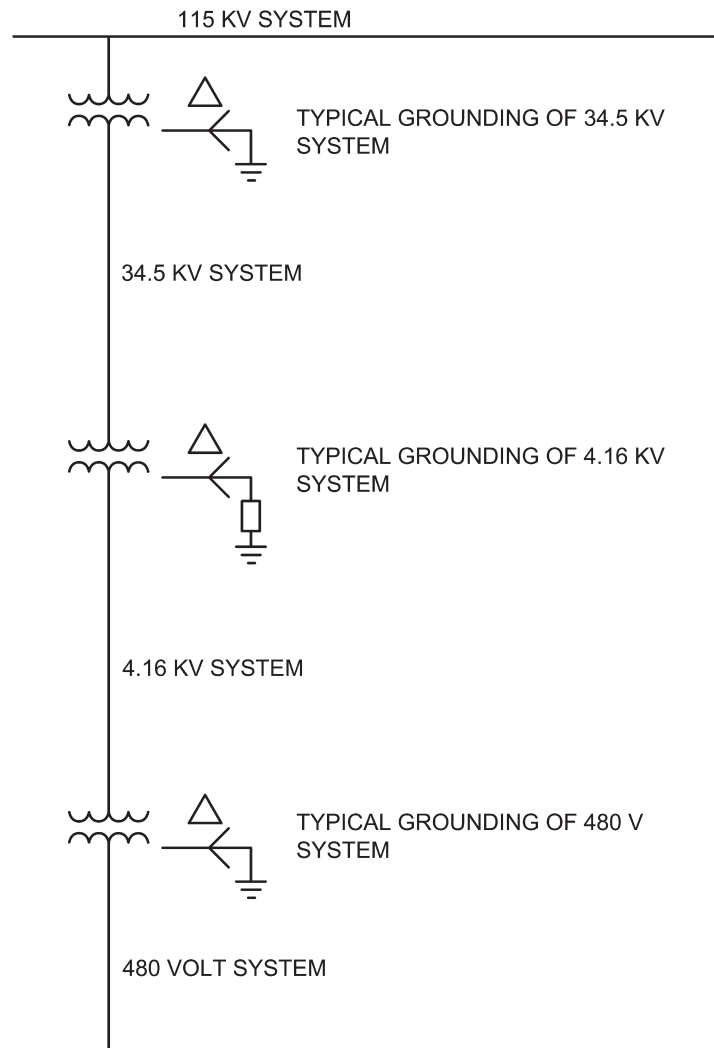


Figure 10—Independent grounding of each voltage level

4.3 Resistance grounding

In a resistance-grounded system, the neutral of the transformer or generator is connected to ground through a resistor. A typical resistance-grounded neutral system is shown in [Figure 11](#). As commonly installed, the resistance has a considerably higher ohmic magnitude than the system reactance at the resistor location. Consequently, the line-to-ground-fault current is primarily limited by the resistor itself.

The reasons for limiting the current by resistance grounding include:

- To reduce burning and melting effects in faulted electric equipment, such as switchgear, transformers, cables, and rotating machines.
- To reduce mechanical stresses in circuits and apparatus carrying fault currents.
- To reduce electric-shock hazards to personnel caused by ground-fault currents in the ground-return path.

- d) To reduce the risk of an arc blast or flash hazard to personnel by limiting the energy produced in a single phase-to-ground fault. This will greatly reduce the risk of the fault propagating to a three phase fault.
- e) To reduce the momentary line-voltage dip occasioned by the occurrence and clearing of a ground fault.
- f) To secure control of transient overvoltages while at the same time avoiding the shutdown of a faulted circuit on the occurrence of the first ground fault (high-resistance grounding).

Resistance grounding may be either of two classes, high resistance or low resistance, distinguished by the magnitude of ground-fault current permitted to flow. Although there are no recognized standards for the levels of ground-fault current that define these two classes, in practice there is a clear difference.

Systems grounded through resistors require surge arresters suitable for use on ungrounded neutral circuits. Metal-oxide surge arrester ratings must be chosen so that neither the maximum continuous operating voltage capability nor the one-second temporary overvoltage capability is exceeded under system ground fault conditions.

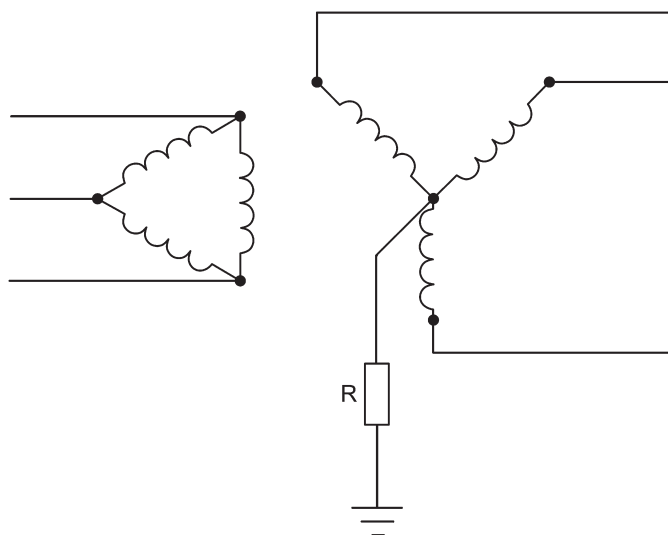


Figure 11—Resistance grounded system

4.3.1 High resistance grounding

High-resistance grounding employs a neutral resistor of high ohmic value. The value of the resistor is selected to limit the current, I_R , to a magnitude equal to or slightly greater than the total capacitance charging current, $3 I_{C0}$, as shown in [Figure 12](#).

Typically, the ground-fault current, I_G , is limited to 10 A or less, although some specialized systems at voltages in the 15 kV class may require higher ground fault levels. In general, the use of high-resistance grounding on systems where the line-to-ground fault exceeds 10 A should be avoided because of the potential damage caused by an arcing current larger than 10 A in a confined space.

Several references [\[B3\]](#) are available which give typical system charging currents for major items in the electrical system. These will allow the value of the neutral resistor to be estimated in the project design stage. The actual system charging current may be measured prior to connection of the high-resistance grounding equipment following the manufacturer's recommended procedures.

High-resistance grounding usually does not require immediate clearing of a ground fault since the fault current is limited to a very low level. The protective scheme associated with high-resistance grounding is usually detection and alarm rather than immediate trip. For this reason, the resistor is rated for continuous operation.

A typical scheme for detecting a ground fault in a high-resistance grounded system is shown in Figure 13, with a resistor connected directly to the neutral of the power source. Under normal operation, the neutral point of the transformer is at near zero potential. When a single line-to-ground fault occurs, the neutral point is raised to approximately line-to-neutral voltage. The resistor is sized to limit the current to the desired value.

An alternative method is shown in Figure 13, where a step-down transformer is typically used to reduce the line-to-neutral voltage of the system to a level acceptable to the protective device. The resistance R_1 is the reflected resistance of R in the secondary of the transformer.

High-resistance grounding has the following advantages:

- Service continuity is maintained. The first ground fault does not require process equipment to be shut down.
- Transient overvoltage due to restriking ground faults is reduced (to 173% of normal line-to-ground potential).
- A pulse system will facilitate locating a ground fault. This is achieved by cyclically altering the resistor in the neutral-to-ground path between two or more values. This in effect will cause the ground-fault current to change. This change can be detected using a zero sequence current sensor to follow the faulted path to the very point of the fault. The fault signature will be present only in the faulted path.
- Flash hazards to personnel associated with high ground-fault currents are eliminated.
- The need for and expense of coordinated ground fault relaying is eliminated.

High-resistance grounding is generally employed in the following:

- Low voltage (where permitted), i.e., commercial and industrial locations where there are no line-to-neutral loads.
- Medium voltage systems where capacitive charging current is not excessive.
- Retrofits of previously ungrounded systems where it is desired to reduce transient overvoltages potentially caused by restriking ground faults.
- For protection of generator windings.

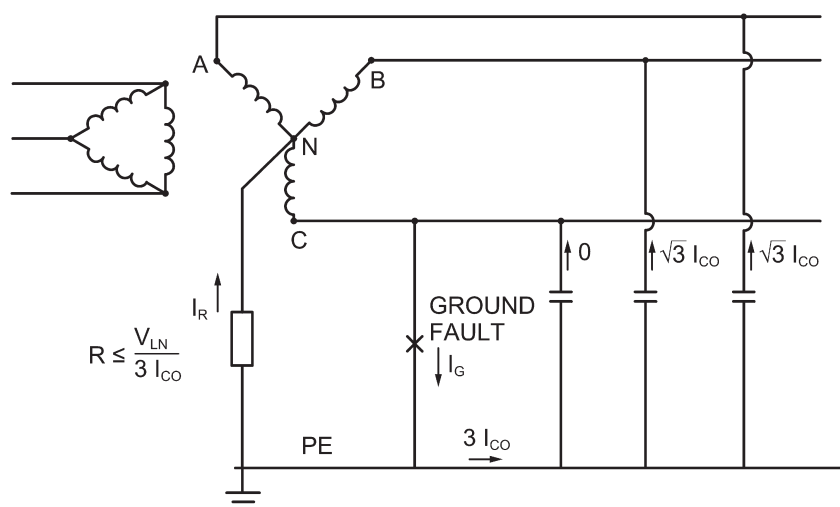


Figure 12—Single line-to-ground fault on a high-resistance grounded system

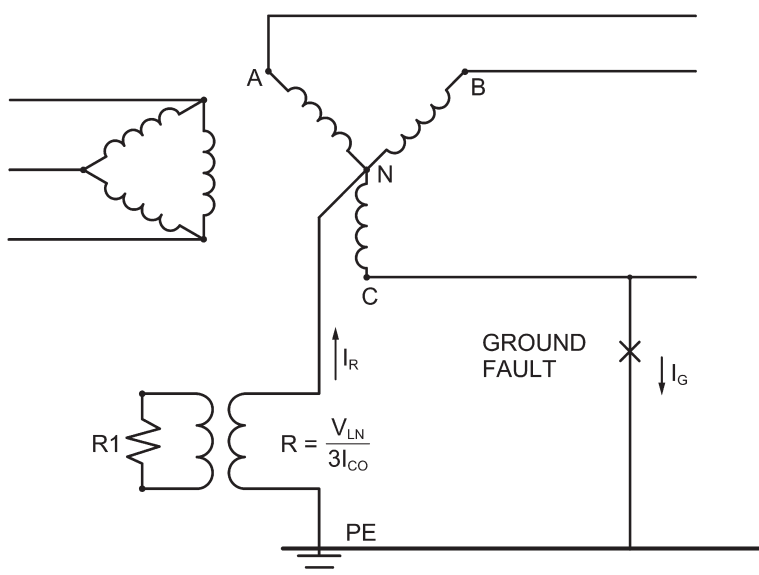


Figure 13—Scheme for ground fault on a high-resistance grounded system using voltage transformer

4.3.2 Low-resistance grounding

Low-resistance grounding is designed to limit ground-fault current to a range between 50 A and 1000 A. The level of fault current is optimally chosen as the lowest value that helps ensure reliable tripping of protective devices with 400 A being typical. The neutral resistor, R , shown in Figure 14, is selected according to $R = V_{LN} / I_G$, where V_{LN} is the system line-to-neutral voltage and I_G is the desired ground-fault current.

Figure 15 illustrates the flow of currents for a single line-to-ground fault on a low resistance grounded system. Since the combined effects of charging current and system source impedance will affect the ground current value less than 0.5% in the typical range of utility supplied systems, ignoring these effects in calculating the ground fault resistance value is permissible. The general practice is to consider that the full system line-to-

neutral voltage appears across the grounding resistor. Only in the case of systems supplied by small generators should departure from this general practice be considered.

Low-resistance grounding has the advantage of facilitating the immediate and selective clearing of a grounded circuit. This requires that the minimum ground-fault current be large enough to be detected by ground fault relay. When a ground fault occurs, the neutral potential is raised to approximately line-to-neutral voltage, resulting in current flow through the resistor. Upon indication that a ground fault has occurred, action would be initiated to disconnect the transformer from the secondary circuit.

Since the intent is that the ground-fault current supplied by low-resistance grounding be promptly and automatically cleared by protective relaying, the grounding resistor can be rated for intermittent duty. Normal practice is to rate it for 10 s or 30 s, depending upon the degree of security appropriate for the application. In cases of faults that are not, or cannot be, disconnected by secondary breakers, the ability for prompt and automatic disconnection of the primary source is required. Suitable relaying and switching devices for this purpose are an integral part of the low-resistance system design.

Low-resistance grounding finds application in medium voltage systems of 35 kV and below, particularly where large rotating machinery is used. By limiting ground-fault currents to hundreds of amperes, instead of thousands of amperes, damage to expensive equipment is reduced.

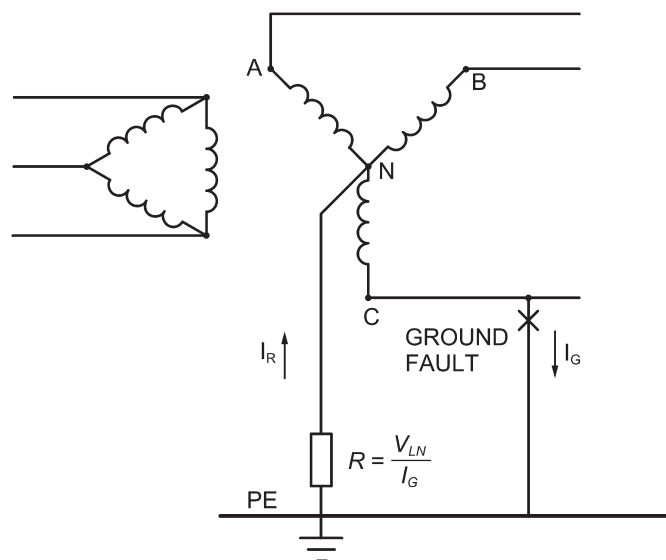


Figure 14—Low-resistance grounded system



Figure 15—Single line-to-ground fault on a low-resistance grounded system

4.3.3 Hybrid grounding

The hybrid grounding scheme combines both high-resistance (HRG) and low-resistance grounding (LRG) as shown in Figure 16 (hybrid high-resistance grounding = HHRG). The scheme adaptively switches the grounding in the generator neutral to HRG when a generator ground fault is detected by opening a high-speed switch to remove the LRG source.

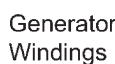


Figure 16—Generator hybrid ground

The need for hybrid grounding stems from the two contributors to internal fault current, the system and the generator itself. The system fault current contribution is quickly interrupted when the generator breaker is tripped after a four to six-cycle delay, which assumes a three or five-cycle breaker, respectively, with one cycle of relay time. Figure 17 plots the watt-second energy from both sources of ground-fault current. It can be seen from this plot that the vast majority of damage occurs from the generator current source after tripping has occurred. Even with one cycle fault recognition, the resulting fault decay time of the generator current results in the vast majority of damage. The more system sources of ground current, the higher the energy will be from the system contribution; but clearly if fault damage is to be reduced, the contribution from the generator must be reduced [B28], [B29], [B31], [B32].

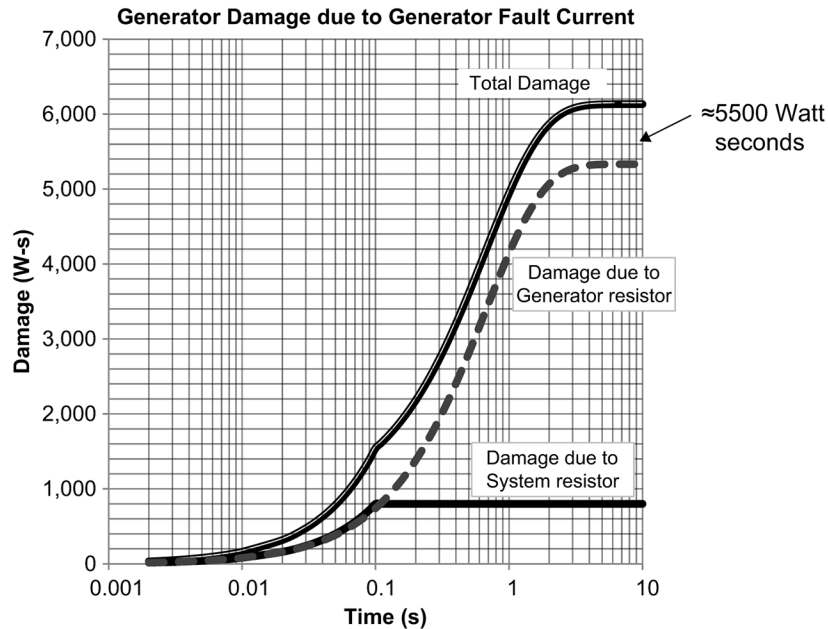


Figure 17—Watt-second fault energy versus time

Simply high-resistance grounding the generator is not a viable option because during emergency situations when the utility source is unavailable when the utility breaker is open and the generator can be the sole source of power to the industrial facility shown in Figure 18. A sufficient level of ground current must be maintained to;

- Stabilize neutral shift on the un-faulted phases
- Provide enough ground current to allow proper operation of ground fault protection on the industrial system

Those objectives require a ground current in the range of 200 A to 1000 A. Only for internal generator ground faults is the high-speed switch tripped to change the grounding scheme from low resistance to high resistance.

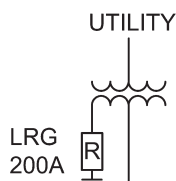


Figure 18—Typical hybrid grounding schematic

4.4 Reactance grounding

The term reactance grounding describes the case in which a reactor is connected between the system neutral and ground, as shown in [Figure 20](#). Since the ground fault that may flow in a reactance-grounded system is a function of the neutral reactance, the magnitude of the ground-fault current is often used as a criterion for describing the degree of grounding. In a reactance-grounded system, the available ground-fault current should be at least 25% ($X_0 = 10X_1$) and preferably 60% ($X_0 = 3X_1$) of the three-phase fault current to prevent serious transient overvoltages. The term X_0 , as used, is the sum of the source zero-sequence reactance, X_{0s} , plus three times the grounding reactance, $3X_N$, ($X_0 = X_{0s} + 3X_N$). This value is considerably higher than the level of fault current desirable in a resistance-grounded system, and therefore reactance grounding is usually not considered an alternative to low-resistance grounding. Reactance grounding is typically reserved for applications where there is a desire to limit the ground fault duty to a magnitude that is relatively close to the magnitude of a three-phase fault. Use of neutral grounding reactors to provide this fault limitation will often be found to be a less expensive application than use of grounding resistors if the desired current magnitude is several thousand amperes.

These circumstances may arise in one of two possible instances. One potential setting is where a large substation feeds a medium voltage distribution system, and the total zero sequence impedance of the step-down transformers in the station causes the single-line-to-ground-fault current to greatly exceed the magnitude of a three-phase fault, and ground fault limitation is desired to keep the total fault current within the reasonable limits. These conditions tend to occur most often in electric utility distribution practice.

The second instance is where there is a desire to serve single-line-to-neutral-connected load directly at the terminal voltage of generators, i.e., without an intervening generator isolation transformer. In this instance, a current will flow in the generator neutral as a result of unbalance between the loads on the three phases. A resistor in the neutral circuit of the generator will limit the flow of this unbalance, thereby limiting the ability of the system to carry unbalanced single-phase load. Medium voltage generators are typically not designed to withstand the unbalanced mechanical forces associated with supplying ground-fault currents that exceed the magnitude of current that the machine would produce to a three-phase fault at its terminals, thereby making solid grounding of the neutral undesirable. Use of low-reactance grounding to limit the ground fault magnitude to a level slightly lower than the three-phase level is a way to resolve these application constraints. The conditions that favor low-reactance grounding of generators are relatively rare, so this practice is somewhat obscure.

4.5 Resonant grounding (ground-fault neutralizer)

A ground-fault neutralizer is a reactor connected between the neutral of a system and ground. The reactor, X_L , is specially selected, or tuned, to resonate with the distributed capacitance, X_{C0} of the system so that a resulting ground-fault current is resistive and low in magnitude. A resistance, r , is shown depicting reactor losses. The resulting ground-fault current is in phase with the line-to-neutral voltage so that current zero and voltage zero occur simultaneously. If the ground fault is in air, such as an insulator flashover, it may be self-extinguishing.

Operation of a ground-fault neutralizer is explained with reference to Figure 19. The distributed capacitance per phase is assumed to be balanced. When one phase of the system is grounded (assume phase C) a line-to-neutral voltage, V_{CN} , is impressed across the reactor. This produces a lagging inductive current, I_L , that flows from the neutralizer through the transformer, to the fault, then to the ground. At the same time a leading capacitive current, $3 I_{C0}$, flows from the two unfaulted lines through the capacitance to ground and to the fault. The lagging current from the inductor and the leading current from the distributed capacitance are practically 180° out of phase. By properly tuning the reactor (selecting the right tap), the inductive and capacitive components of current can be made to neutralize each other, leaving only a relatively small component of resistive current, I_r , to flow in the fault.

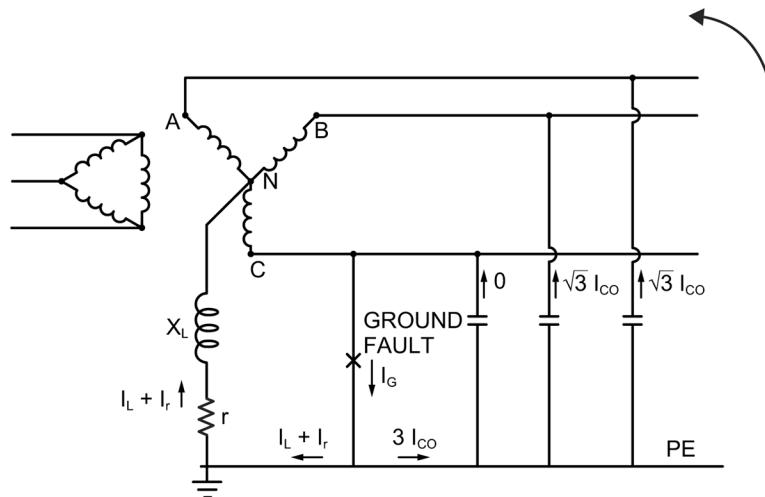


Figure 19—Single line-to-ground fault on a reactance-grounded system

This method of grounding was occasionally seen in high-voltage transmission practice. Today, it is rarely encountered in North America. There are a few instances in which it has been applied for generator grounding in large central stations, especially in the New England area. However, it is relatively common in electric utility distribution practice in the UK and Europe. A key requirement is that because the resonant circuit must be retuned if the distributed parameters of the associated circuit are changed, the ideal application is one that does not involve frequent circuit switching or reconfiguration.

4.6 Solid grounding

Solid grounding refers to the connection of a system conductor, usually the neutral of a generator, power transformer, or grounding transformer directly to ground, without any intentional intervening impedance. Two examples of solidly grounded systems are shown in Figure 20. Acknowledging the impedance of the source and the unintentional impedance in the connection to ground leads to reference of these systems as effectively grounded.

To assess the benefits of a solid connection to ground, determining the degree of grounding provided in the system is necessary. A good guide in answering this question is the magnitude of ground-fault current as compared to the system three-phase fault current. The higher the ground-fault current in relation to the three-phase fault current, the greater the degree of grounding in the system. Effectively grounded systems are systems whose line-to-ground short-circuit current (I_{SLG}) is at least 60% of the three-phase, short-circuit value (I_{3ph}).

4.6.1 Effectively grounded

A system is effectively grounded when grounded through a sufficiently low impedance (inherent or intentionally added, or both) so that the coefficient of grounding (COG) does not exceed 80%. The term coefficient of grounding (COG) is defined as the ratio of E_{LG}/E_{LL} , expressed as a percentage, of the highest rms line-to-ground power frequency voltage (E_{LG}) on an unfaulted phase, at a selected location, during a fault to earth affecting one or more phases to the line-to-line power frequency voltage (E_{LL}) that would be obtained, at the selected location, with the fault removed. Coefficient of grounding may be calculated from the known impedances of the system and the fault.

This value is obtained approximately when, for all system conditions, the ratio of the zero-sequence reactance to the positive-sequence reactance, (X_0/X_1), is positive and ≤ 3 , and the ratio of zero-sequence resistance to positive-sequence reactance, (R_0/X_1), is positive and < 1 .

In formulae:

$I_{SLG} \geq 0.6 I_{3ph}$. Thus:

$$3E / (X_0 + 2X_1) \geq 0.6E / X_1$$

hence,

$$X_0 / X_1 \leq 3$$

Further condition is $R_0 < X_1$

The X_1 component used in the above equations is the Thevenin equivalent positive-sequence reactance of the complete system, including the subtransient reactance of all rotating machines; R_0 and X_0 are the Thevenin equivalent zero sequence resistance and reactance of the complete system. The above equations must exist at all points in the system. This is seen in [Figure 20](#).

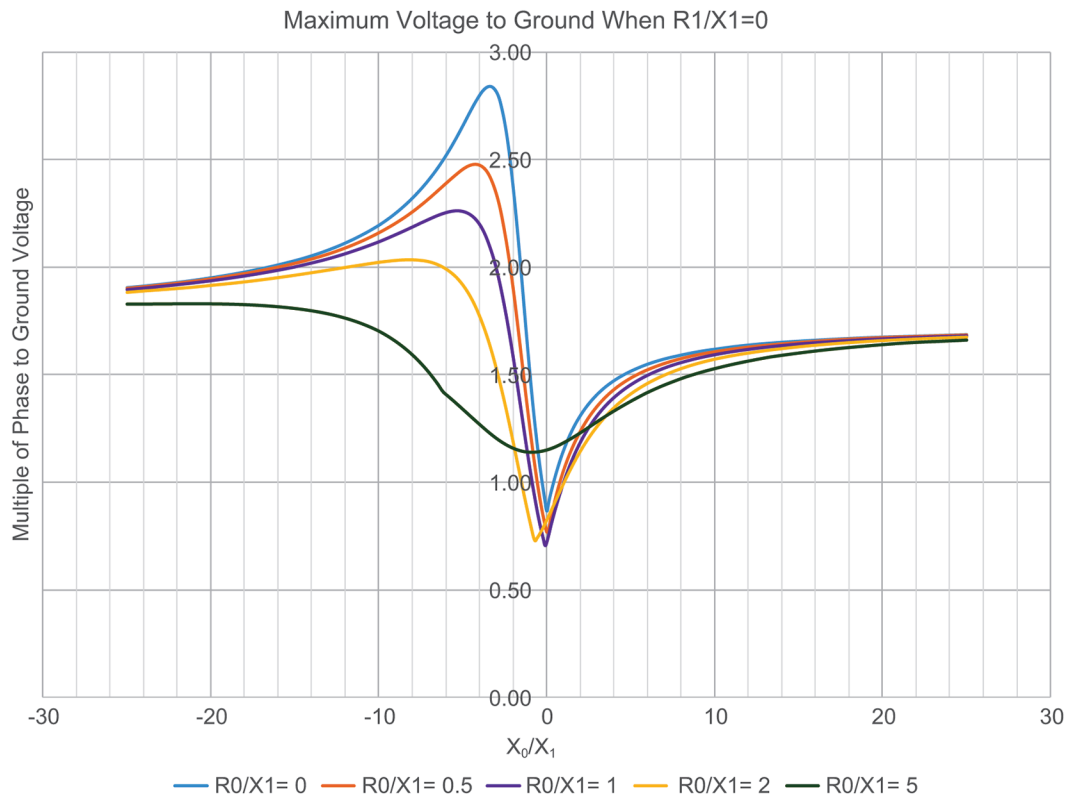


Figure 20—Transient overvoltage

Because the reactance of a solidly grounded generator or transformer is in series with the neutral circuit, a solid connection does not provide a zero impedance circuit. If the reactance of the system zero-sequence circuit is too great with respect to the system positive-sequence reactance, the objectives sought in grounding, principally freedom from transient overvoltages, may not be achieved. If R_0 is too high, it may not create transient voltages, but it may also not provide desired suppression of voltage to ground on the unfaulted phases.

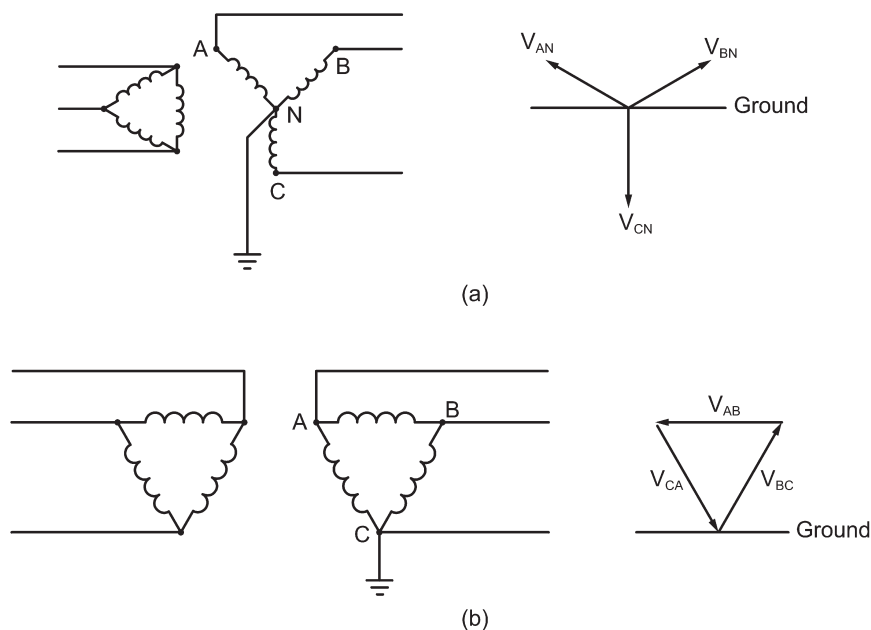


Figure 21—Solidly grounded systems a) Grounded wye b) Corner grounded delta

This condition is rarely a problem in typical industrial and commercial power systems. A sufficiently low resistance to earth may be difficult to achieve, but the ground to which faults occur will be the bonded conductive electrical enclosures. The zero-sequence impedance of most generators used in these systems is much lower than the positive-sequence impedance of these generators. The zero-sequence impedance of a delta-wye transformer will not exceed the transformer's positive-sequence impedance. There are, however, conditions under which relatively high zero-sequence impedance may occur.

One of these conditions is a power system fed by several generators and/or transformers in parallel. If the neutral of only one source is grounded, it is possible for the zero-sequence impedance of the grounded source to exceed the effective positive-sequence impedance of the several sources in parallel.

Another such condition may occur where power is distributed to remote facilities by an overhead line without a metallic ground return path. In this case, the return path for ground-fault current is through the earth, and even though both the neutral of the source and the non-conducting parts at the load may be grounded with well-made electrodes, the ground return path includes the impedance of both of these grounding electrodes. This impedance may be significant. Another significant source of zero-sequence impedance is the large line-to-ground spacing of the overhead line.

Solid grounding is generally recommended for the following:

- a) Low-voltage systems (750 V and below) where automatic isolation of a faulted circuit can be tolerated.
- b) Medium- or high-voltage systems (above 15 kV) in order to permit the use of equipment with insulation levels to ground rated for less than line-to-line voltage.
- c) Medium- or high-voltage applications where the desire for a higher magnitude of ground-fault current in order to be able to provide selective ground fault detection on lengthy distribution feeders outweighs concerns about arc flash and potential gradients as personnel hazards in a workplace setting.

4.7 Characteristics of grounding methods

The advantages and disadvantages of the various methods of grounding are summarized in Table 1.

Table 1—Characteristics of grounding methods

	Ungrounded	Solid	Reactance grounding		Ground-fault neutralizer ^a	Resistance grounding	
			Low value reactor	High value reactor		Low resistance	High resistance
Current for phase-to-ground fault in percent of three-phase fault current	Less than 1%	Varies, may be 100% or greater	Usually designed to produce 25% to 100%	5% to 25%	Nearly zero fault current	20% and downward 100 A to 1000 A	Less than 1% but not less than system charging current, $3I_{co}$
Transient	Very high	Not excessive	Not excessive	Not excessive	Not excessive	Not excessive	Not excessive
Line-to-neutral loads	Not supported	Supported	Supported if current 60% or greater	Not supported	Not supported	Not supported	Not supported
Surge arresters	Ungrounded-neutral type				Ungrounded-neutral type		
Remarks	Not recommended due to overvoltages and nonsegregation of fault	Generally used on systems (1) 600 V and below and (2) over 15 kV		Not used due to excessive overvoltages	Best suited for application in most medium voltage industrial and commercial systems that are isolated from their electric utility system by transformers.	Generally used on systems of 2.4 Kv to 15 kV particularly where large rotating machines are connected	Used on systems up to 5 kV

^aCaution should be applied in using this form of grounding with industrial generation (see IEEE Std 367). This form of grounding is ideal for use on medium-voltage generators. Also occasionally found on mission-critical 2.4 kV or 4.16 kV industrial or commercial distribution systems.

5. Obtaining the system neutral

Locating a point at a source of electrical power to which a connection to ground may be attached is generally desirable. There are several exceptions (e.g., 3 wire delta, 4 wire delta) that are covered later. The most common location is the system neutral point. It should be noted that the neutral point is used for the purpose of system grounding. The fact that there is a neutral point does not imply that a neutral conductor, for the purpose of supplying single-phase loads, can be or should be connected to the neutral point.

While resistance grounding provides increased safety, it precludes operation of line-to-neutral loads. Where single-phase loads are determined to be necessary or desirable, one alternative is to develop a new solidly grounded system that is supplied from the original resistance grounded system, as shown in Figure 22. A delta-wye transformer can be inserted to obtain the system neutral for grounding purposes in three-phase systems. The neutral is then readily available with the added advantage in applications like lighting and enabling use of breakers and panels with reduced short circuit ratings. Such transformers are available for

practically all voltages except 240 V. (240 V transformers typically have a delta secondary with a grounded split phase winding on one side. See 5.2.2.) On new systems, 208Y/120 V or 480Y/277 V, delta-wye-connected transformers may be used to good advantage. Wye-connected source transformers for 2400 V, 4160 V, and 13 800 V systems are commonly available, while other voltages, such as 4800 V or 6900 V, may be available as options. The alternative is grounding transformers.

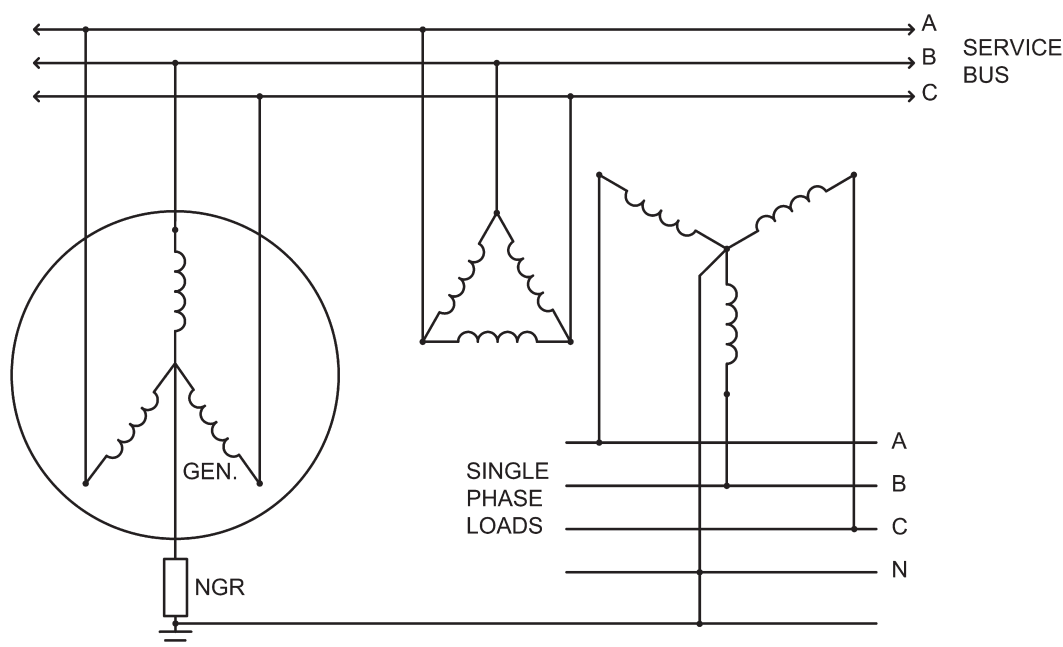


Figure 22—Transformer to obtain neutral where system is resistance grounded

5.1 Grounding transformers

System neutrals may not be available, particularly in many older systems rated 600 V or less and in many existing 2400 V, 4800 V, and 6900 V systems. When existing delta connected or ungrounded systems are to be grounded, grounding transformers can be used to obtain a neutral. The most commonly used grounding transformers are the zigzag and wye-delta type.

5.1.1 Zigzag grounding transformers

One type of grounding transformer commonly used is a three-phase zigzag transformer with no secondary winding. The internal connection of the transformer is illustrated in Figure 23. The impedance of the transformer to balanced three-phase voltages is high so that when there is no fault on the system, only a small magnetizing current flows in the transformer winding. The transformer impedance to zero-sequence voltages, however, is low so that it allows high ground-fault currents to flow. The transformer divides the ground-fault current into three equal components; these currents are in phase with each other and flow in the three windings of the grounding transformer. The method of winding is seen from Figure 23 to be such that when these three equal currents flow, the current in one section of the winding of each leg of the core is in a direction opposite to that in the other section of the winding on that leg. This tends to force the ground-fault current to have equal division in the three lines and accounts for the low impedance of the transformer-to-ground currents.

A zigzag transformer may be used for effective grounding, or an impedance can be inserted between the derived neutral of the zigzag transformer and ground to obtain the desired method of grounding.

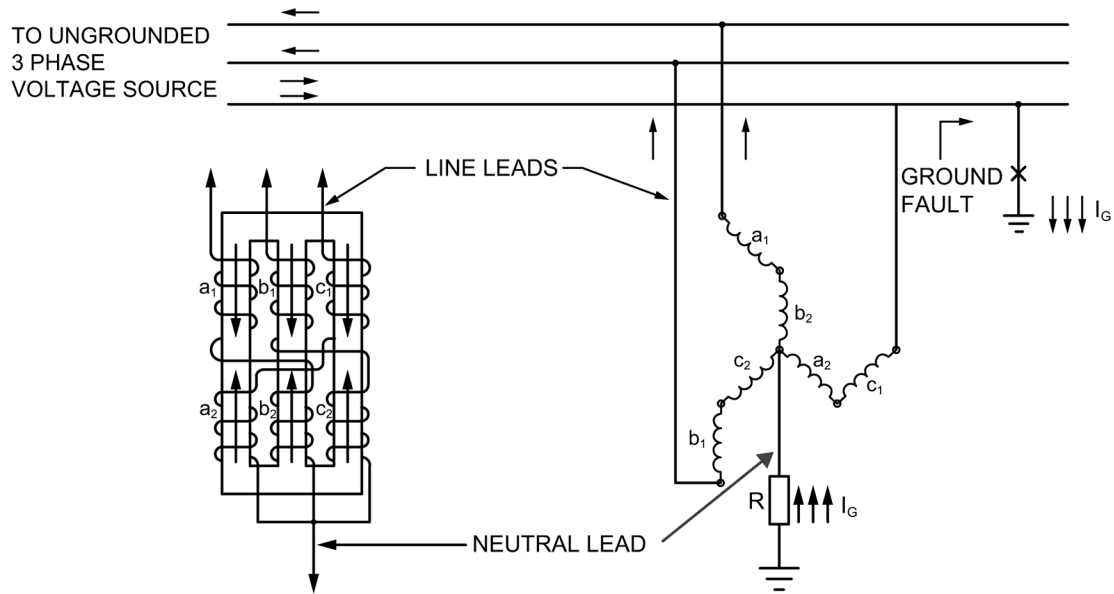


Figure 23—Zigzag grounding transformer a) Core windings b) System connection

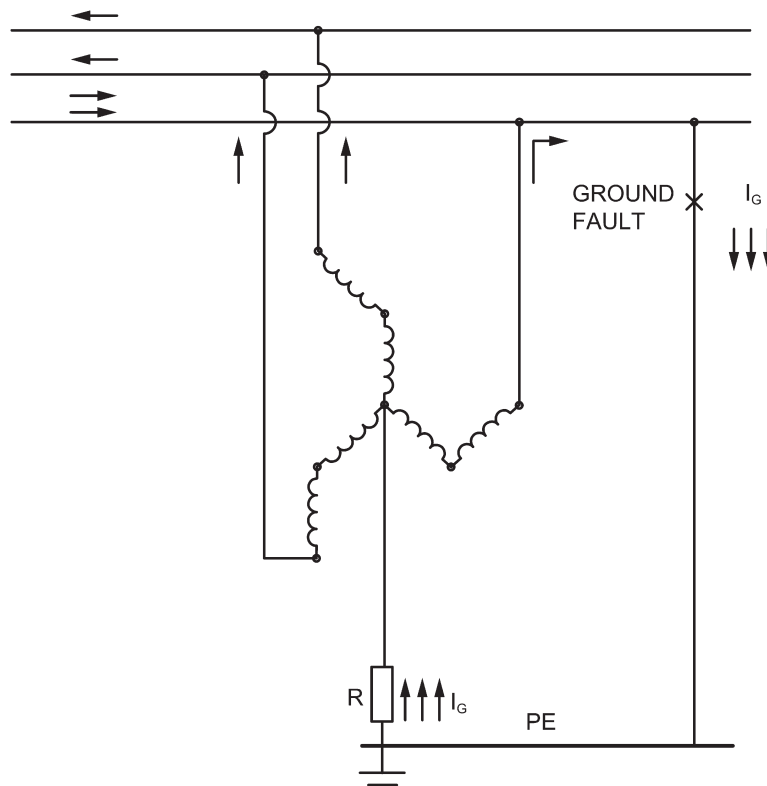


Figure 24—Resistance grounding of a system through a zigzag grounding transformer

5.1.2 Wye-delta grounding transformers

A wye-delta connected three-phase transformer or transformer bank can also be utilized for system grounding, as shown in [Figure 25](#). As in the case of the zigzag transformer, it can be used for effective grounding or to accomplish resistance-type grounding of an existing ungrounded system. The delta connection must be closed to provide a path for the zero-sequence current, and the delta voltage rating is selected for any standard value. A resistor inserted between the primary neutral and ground, as shown in [Figure 24](#), provides a means for limiting ground-fault current to a level satisfying the criteria for resistance-grounded systems. For this arrangement, the voltage rating of the wye winding need not be greater than the normal line-to-neutral system voltage. For the wye-broken delta grounding configuration, the grounding bank must consist of three single-phase transformers with the primary wye neutral connected directly to ground. The secondary delta is closed through a resistor that effectively limits the primary ground-fault current to the desired low level. For this alternative application, the voltage rating of each of the transformer windings forming the wye primary should not be less than the system line-to-line voltage.

The rating of a three-phase grounding transformer or bank, in kilovolt ampere (kVA), is equal to the rated line-to-neutral voltage in kilovolts times the rated neutral current. Most grounding transformers are designed to carry their rated current for a limited time only, such as 10 s or 1 min. Consequently, they are much smaller in size than an ordinary three-phase continuously rated transformer with the same rating.

It is generally desirable to connect a grounding transformer directly to the main bus of a power system without intervening circuit breakers or fuses. This prevents the transformer from being inadvertently removed from service by the operation of the intervening devices. (In this case, the transformer is considered part of the bus and is protected by the relaying applied for bus protection.) Alternatively, the grounding transformer should be served by a dedicated feeder circuit breaker, as shown in part a) of [Figure 27](#), or connected between the main transformer and the main switchgear, as illustrated in part b) of [Figure 27](#). If the grounding transformer is connected as shown in part b) of [Figure 27](#), there should be one grounding transformer for each delta-connected bank supplying power to the system, or enough grounding transformers to assure at least one grounding transformer on the system at all times. When the grounding transformer is so connected, it is included in the protective system of the main transformer.

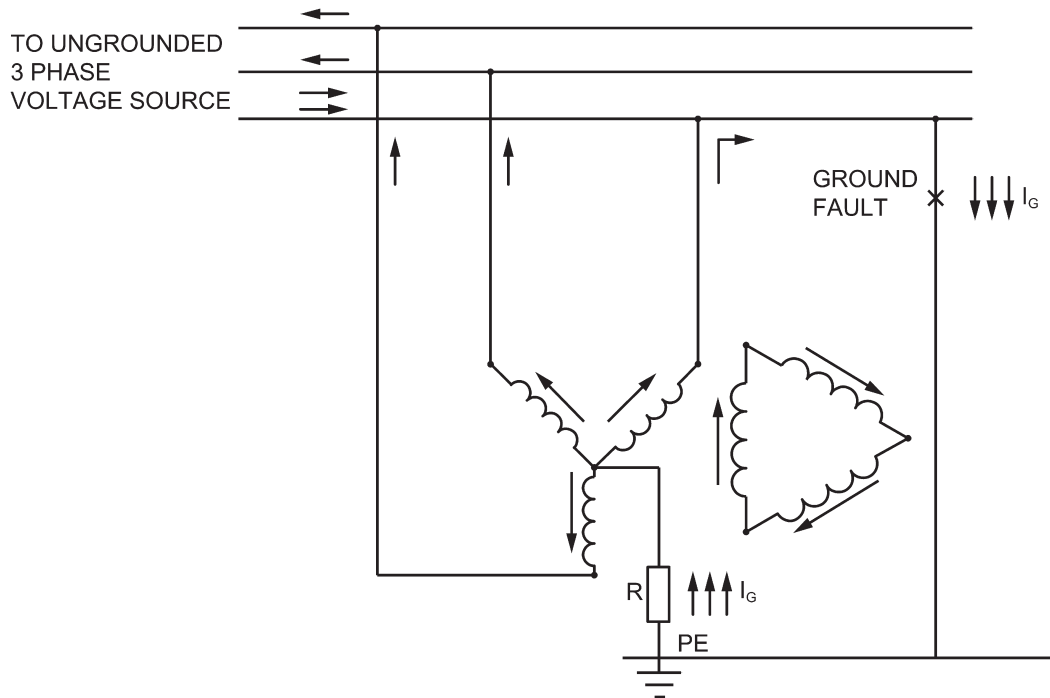


Figure 25—Low-resistance grounding of a system through a wye-delta grounding transformer with ground sensing current relay

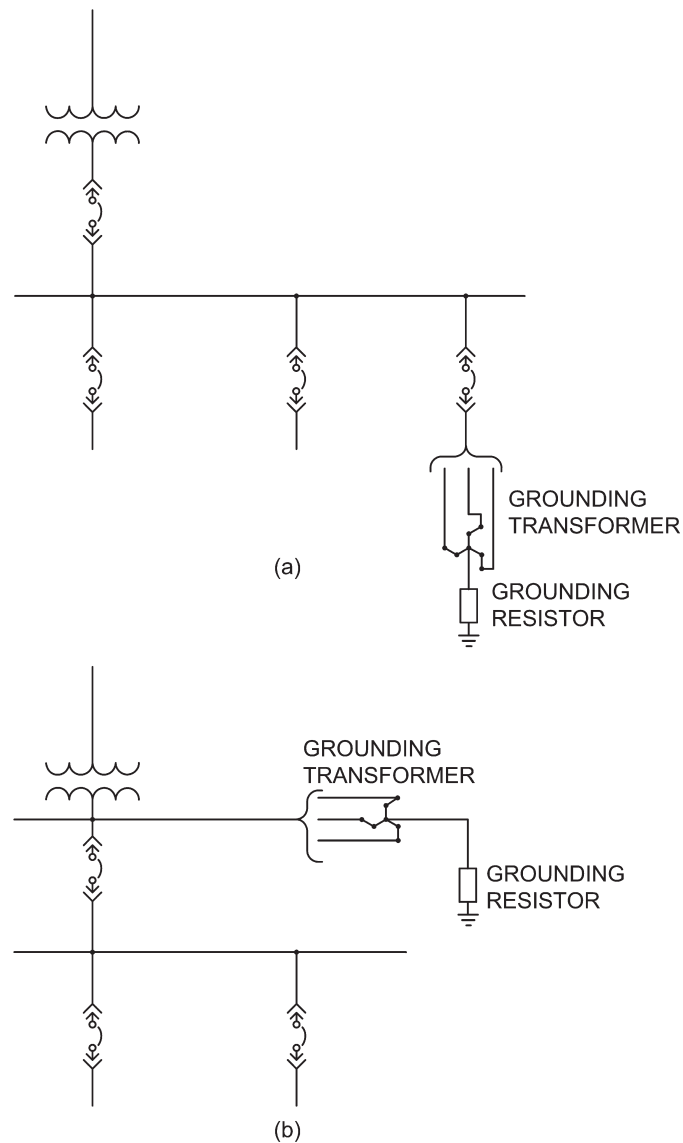


Figure 26—Connection of grounding transformers in delta connected or ungrounded power system to obtain neutral for system grounding a) Circuit feeder breaker b) Connected between main transformer and main switchgear

5.2 Grounding at points other than system neutral

In some cases, low-voltage systems (600 V and below) are grounded at some point other than the system neutral to obtain a grounded electrical system. This approach is done because delta transformer connections do not provide access to the three-phase system neutral. Two systems are in general use.

5.2.1 Corner-of-the-delta grounded systems

Some low-voltage, ungrounded systems have been conceived, as shown previously in part b) of [Figure 21](#), using delta connected supply transformers with no readily available neutral grounding. Voltages to ground of other than the grounded corner are line-to-line values requiring derating of circuit breakers along with cable

insulation ratings of 173%. Because of its limitations, this type of grounding is no longer popular and is not widely used in industrial systems.

5.2.2 One phase of a delta system grounded at midpoint

In some areas where the utility has both a single-phase 120/240 V load and three-phase 240 V loads, they have supplied a larger single-phase 120/240 V transformer and one or two smaller 240 V transformers. (One small transformer is used in an open delta configuration for maximum savings.) All transformers are connected in delta with the midpoint of the 120/240 V grounded for a 240/120 V three-phase four wire system. This provides neutral grounding for the single-phase 120/240 V and also grounding for the 240 V three-phase system. It is not recommended for voltages over 240 V.

The advantages of this type of grounding scheme are:

- First cost for transformers and overcurrent protection can be less than for separate single phase transformers and three-phase systems.
- Mid-phase grounding effectively controls, to safe levels, the transient overvoltages to ground.
- These diverse loads can be served from a single service.

The disadvantages are:

- The shock hazard of the high phase leg to ground is 208 V, which is 1.73 times the voltage of a neutral grounded 240 V system. Since this voltage can appear across a single pole of a breaker, 277 V rated breakers may be required.
- There must be positive identification of the conductor with the highest voltage to ground to avoid connecting 120 V loads to that conductor.
- The fault currents on the single-phase system may be higher than normally expected for the size of the system, possibly requiring higher rated panelboards.

6. Location of system grounding points

6.1 Derived systems

Each system as described in this recommended practice is characterized by its isolation from adjacent systems, whether grounded or ungrounded. The isolation is provided either by the electrical isolation of transformer primary and secondary windings or by the physical isolation of generator windings. This approach does not preclude considering separate power sources, connected in parallel, to have each one separately grounded. Generators and/or transformers are often connected in parallel for increased reliability or to increase the available system power. The secondary of a transformer, with no electrical connections to the primary has derived a new separate system. Similarly, a generator is a separate system having no electrical connection to any other system. The term “separately derived” is generally defined as one whose power is derived from a generator, transformer, or converter windings and that has no direct electrical connection, including a solidly connected grounded circuit conductor, to supply conductors originating in another system. The new derived system created by a transformer or generator should then be considered for grounding and type of grounding depending upon the application requires the establishment of a new system ground if it is required or desired that this system be grounded. The system ground point should generally be located at the power source in order to minimize the impedance in the lightning current path to the earth and to minimize the impedance in higher voltage fault currents thus permitting faster fault current clearing.

6.2 Transformer configurations

While corner grounded deltas or midpoint grounds provide a reference to earth, line-to-ground voltages approaching line-to-line values preclude operation of typical line-to-line loads. There are two requirements that must be met for a transformer to provide a functional system ground. The first requirement is fairly intuitive; the transformer winding at the voltage where a ground is desired must be connected in wye (sometimes referred to as star in European practice). Alternatively, transformers with windings connected in the interconnected star or zigzag configuration also provide a neutral point that can be grounded.

The second requirement is a bit more involved. Table 1 lists a number of options for the mode of system grounding. In order for these options to exist, the impedance of the transformer to ground-fault current must be significantly lower than the impedance of the connection between the neutral and earth such that this neutral impedance governs the selection of grounding mode [B15]. Essentially, this configuration translates into a requirement that the transformer contain a second winding that is connected in delta. Thus, a transformer that is intended to provide a system ground must provide a wye-connected winding at the voltage of the system to be grounded, and must also contain a delta winding. The most common configuration that meets this requirement in industrial and commercial applications is a transformer that has a delta-connected primary winding and a wye-connected secondary winding.

Wye-wye transformers alone cannot be used to enable a separately derived system ground for industrial and commercial power systems. In special cases, using wye-wye transformers that are equipped with delta-connected tertiary windings to provide system grounding is possible. This arrangement can be designed for low-resistance grounding as well as effective grounding. It is also possible to use wye-connected autotransformers provided they also have a delta-connected tertiary winding, although this is a relatively uncommon practice and should only be used to provide effective (solid) grounding. Applying a neutral grounding resistor between ground and the neutral of autotransformers can lead to undesirable neutral voltage excursions.

Using wye-wye connected transformers with special five-leg magnetic cores to serve commercial applications on effectively grounded (utility) distribution systems is a common practice. This connection is chosen to address concerns with ferroresonance that come about due to single-phase switching (it is a common practice that utility distribution systems use single point load-break switching devices, typically hook-stick operated), and this connection minimizes concerns with ferroresonance that would otherwise be present in that situation. Rather than provide system grounding itself, the five-leg core wye-wye transformer provides a continuous path for ground-fault currents from the primary distribution system into the commercial load on the secondary. The system ground is actually established by the transformer that supplies the host distribution system. This practice results in the commercial system also being effectively grounded.

6.2.1 Delta-wye transformer

In a delta-wye connected transformer, with the load side neutral grounded, zero-sequence components of current can flow in the secondary wye-connected windings due to a ground fault. Zero-sequence current is then induced into the primary windings of the transformer and circulates in the delta connection. Positive and negative-sequence currents pass through the transformer combining to produce high current in two of the primary phase conductors. A ground fault on the secondary of the delta-wye connected transformer appears as a line-to-line fault on the primary.

If the neutral of the wye-connected windings is not grounded, then zero-sequence current cannot flow and the system becomes ungrounded.

	SYMBOLS	CONNECTION DIAGRAMS	ZERO-SEQUENCE EQUIVALENT CIRCUITS
(a)			
(b)			
(c)			
(d)			

NOTE—Configurations a) and c) permit the flow of zero-sequence current; b) does not, and d) requires further examination as to the grounding of the source.

Figure 27—Zero-sequence impedance of different transformer configurations

Zero-sequence components of current can flow through a wye-wye connected transformer if a neutral path exists on both sides of the transformer. An example is shown in Figure 29, where a delta-wye connected transformer, T_1 , supplies power to a wye-wye connected transformer, T_2 . A fault on the load side of T_2 produces zero-sequence current, which flows in the primary and secondary windings of that transformer. Zero-sequence current is permitted to flow in the primary of T_2 because a path exists in the delta-wye connected transformer T_1 . Disconnecting any of transformer neutrals, on either T_1 or T_2 , would prevent the flow of zero-sequence current in both transformers, except as allowed by magnetizing reactance.

Depending upon the connections to the transformer, the use of a wye-wye transformer can result in a single system, or its load side may be a separately derived system. Figure 29 shows a single system.

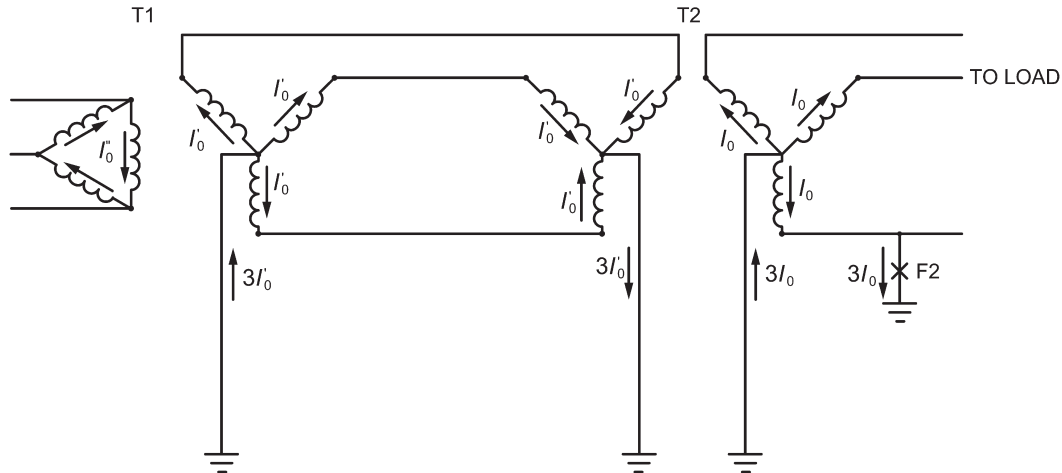


Figure 28—Transformer connections illustrating the flow of zero-sequence current resulting from a line-to-ground fault

6.2.2 Wye-wye transformers

A wye-wye transformer, T_2 , is shown in Figure 29 with the primary and secondary neutrals interconnected through their separate connections to ground. This transformer configuration is used on solidly grounded utility distribution systems, particularly underground systems, to reduce the likelihood of ferroresonance when the supply switches can be operated one phase at a time. The utilities ground the primary neutral point to minimize the neutral-to-earth voltage throughout the length of the distribution line and by default on underground systems using bare concentric neutral cables. They ground the secondary neutral to provide an effectively grounded low-voltage service. Note that this multiple grounding of the primary at each transformer is not essential to prevent ferroresonance or provide secondary grounding as long as the fourth conductor is brought to the primary neutral of the transformer. The neutral-to-transformer case and ground connection minimizes secondary neutral-to-ground voltage during a fault between primary and transformer case.

In an industrial distribution system, the physical length of the circuit will usually be short enough so that excessive neutral-to-ground voltages will not be present even if there is no ground at the wye-wye transformer common neutral terminals, as shown in Figure 29.

The schematic shown in Figure 29 can be considered a separately derived system. If the neutral is grounded at the source, T_1 , the output of the wye-wye transformer will be a continuation of the grounded system, though at the secondary voltage of the transformer. A fault, F_2 , on the load side of the wye-wye connected transformer, T_2 , will produce zero-sequence components of current in its primary windings. This zero-sequence current will flow back to the secondary neutral terminal of source transformer, T_1 .

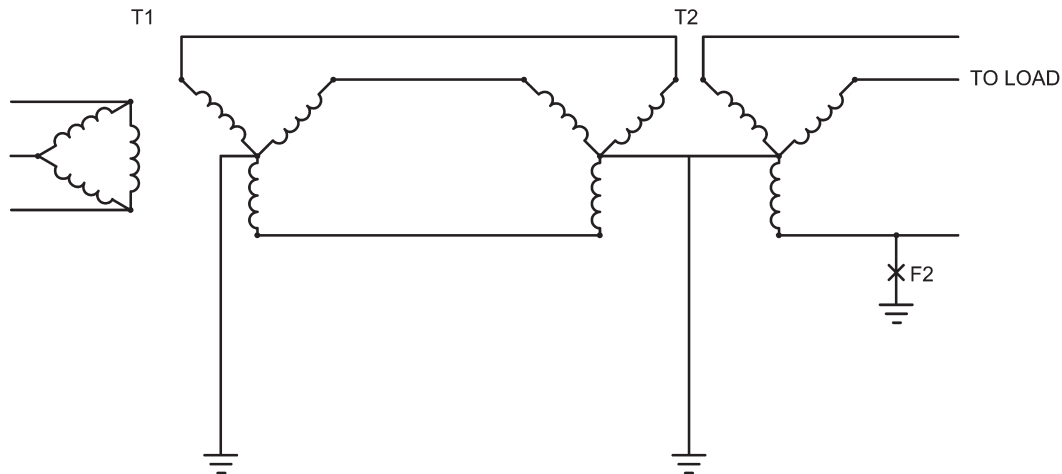


Figure 29—Non separately derived wye-wye transformer

This transformer connection utilizes the standard wye-wye transformer that contains an internal primary-to-secondary neutral connection suitable for utility practices as shown in Figure 29. Wye-wye transformers are typically avoided for industrial and commercial facilities because fault clearing may result in greater system interruption than would otherwise occur with delta-wye transformation.

The circuit supplied by the wye-wye connected transformer shown in Figure 30 cannot be considered a separately derived system since there are no direct metallic connections between the primary and secondary of the transformer. Primary and secondary ground faults are separately measured and relayed. The secondary of the transformer will not be grounded unless a connection to earth is made. The secondary could be impedance grounded. Secondary neutral grounding will also require a connection from the neutral of the primary source to the primary neutral of the wye-wye transformer to supply zero-sequence current. Unlike the delta-wye transformer, the wye-wye transformer itself is not a source of zero-sequence current. Grounding can be achieved without a primary neutral connection if a phase of the secondary rather than the neutral is grounded since no zero-sequence current is involved. The effect is then identical to corner grounding of a delta-delta transformer.

6.3 Single power source

When a system has only one source of power (generator or transformer), grounding may be accomplished by connecting the source neutral to earth either directly or through a neutral impedance as shown in Figure 31. Provision of a switch or circuit breaker to open the neutral circuit is not recommended. Operating the system ungrounded by having the ground connection open while the generator or transformer is in service is not desirable.

In the event that some means of disconnecting the ground connection is required for measurement, testing, or repair, a disconnecting link should be used and only opened when the system is de-energized.

6.4 Multiple power sources

For installation of interconnected multiple power sources (i.e., generators or power transformers) operated in parallel, system grounding can be accomplished using one of the two following methods:

- a) Each source grounded, with or without impedance (see Figure 32).

- b) Each source neutral connected to a common neutral bus, which is then grounded, with or without impedance (see [Figure 33](#)).

For solidly grounded systems with multiple sources where all sources must be solidly grounded, separately ground each power source as shown in part a) of [Figure 31](#) unless third harmonics are present or if it results in exceeding the fault capability of the generators. Levels of fault current in systems where generators are paralleled with transformer sources on a four-wire basis must be calculated using symmetrical component sequence values for the sources appropriately combined in the system [B24]. Commercial computer programs are now available that will calculate branch currents for unbalanced faults in systems with both utility and generator sources. There can be a significant increase in the total system ground-fault current as compared to the sum of the fault current available from sources when not in a combined system, while the increase in generator currents can be proportionally even greater.

Where sources are in close proximity, or where the system is four wire, the common neutral or ground bus as shown in part a) of [Figure 33](#) should be used. In a four-wire system, the sources would not be considered as separately derived. If the power sources are not in close proximity, a common ground point is not recommended. The impedance in the neutral bus connection may become large enough to prevent effectively grounding the neutral of the source at the remote location. The interconnection may inadvertently become open, allowing the transformer to operate ungrounded.

For impedance grounded systems, separately connecting each neutral to ground through an individual impedance [part b) of [Figure 31](#)] is acceptable.

Individual neutral switching devices (automatic or manual) are not recommended since incorrect operation may allow a power source to operate ungrounded.

System relaying is more complex when there are multiple ground fault sources. The fault current sensed by the feeder is variable, depending on the number of ground-fault current sources that are connected at the time of the fault.

When individual source impedances are used for low or high-resistance grounding, circulation of third harmonic currents between paralleled generators is usually not a problem since the impedance limits the circulating current to tolerable values. When the total ground-fault current from several individual impedances exceeds 1000 A, a common ground point and single impedance should be considered to provide a single acceptable value of ground-fault current [part b) of [Figure 33](#)]. The advantage of this connection is that the maximum fault current is known, and selective relaying can be used to open tie breakers and selectively isolate the faulted bus.

The primary purpose of neutral disconnecting devices in impedance grounded systems, as shown in part b) of [Figure 31](#), is to isolate the generator or transformer neutral from the neutral bus when the source is taken out of service because the neutral bus is energized during ground faults. A generator or transformer disconnected from the power bus, but with an unbroken connection of its neutral to the neutral bus, would have all of its terminals elevated with respect to ground during a ground fault. Disconnecting devices should be metal enclosed and interlocked in such a manner as to prevent their operation except when the transformer primary and secondary switches or generator main and field circuit breakers are open. On low-voltage systems, the use of four-pole breakers may provide adequate interlocking. In this case, line-to-neutral voltage should not be used for synchronizing.

In the case of multiple transformers, all neutral isolating devices may be normally closed because the presence of delta-connected windings (which are nearly always present on at least one side of each transformer) minimizes the circulation of harmonic current between transformers. Generators that are designed to suppress zero-sequence harmonics, usually by the use of a two-thirds pitch winding, will have negligible circulating currents when operated in parallel. Therefore, operating these types of generators with the neutral disconnect

device closed is often found practical. This method simplifies the operating procedure and increases assurance that the system will be grounded at all times because interlocking methods can be used.

Operating with only one generator neutral disconnecting device closed at a time to eliminate any circulating harmonic or zero-sequence currents is sometimes desirable. In addition, this method provides control over the maximum ground-fault current and simplifies ground relaying. When the generator whose neutral is grounded is to be shut down, another generator is grounded by means of its neutral disconnecting device before the main and neutral disconnecting device of the first one are opened. This method has some inherent safety considerations that must be recognized and addressed in order to ensure continual safe operation. The procedures required to permit only one disconnecting device to be closed with multiple sources generally do not permit the use of conventional interlocking methods to ensure that at least one neutral disconnecting device will be closed. Therefore, this method should only be used where strict supervision of operating procedures is assured.

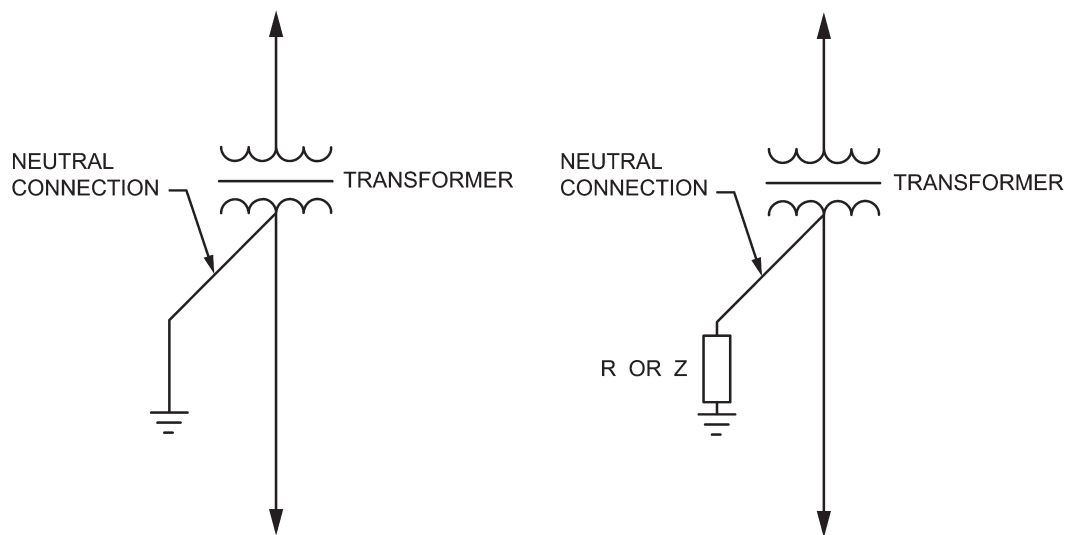


Figure 30—Grounding for systems with one source of power: a) Solidly grounded, b) R or Z grounded

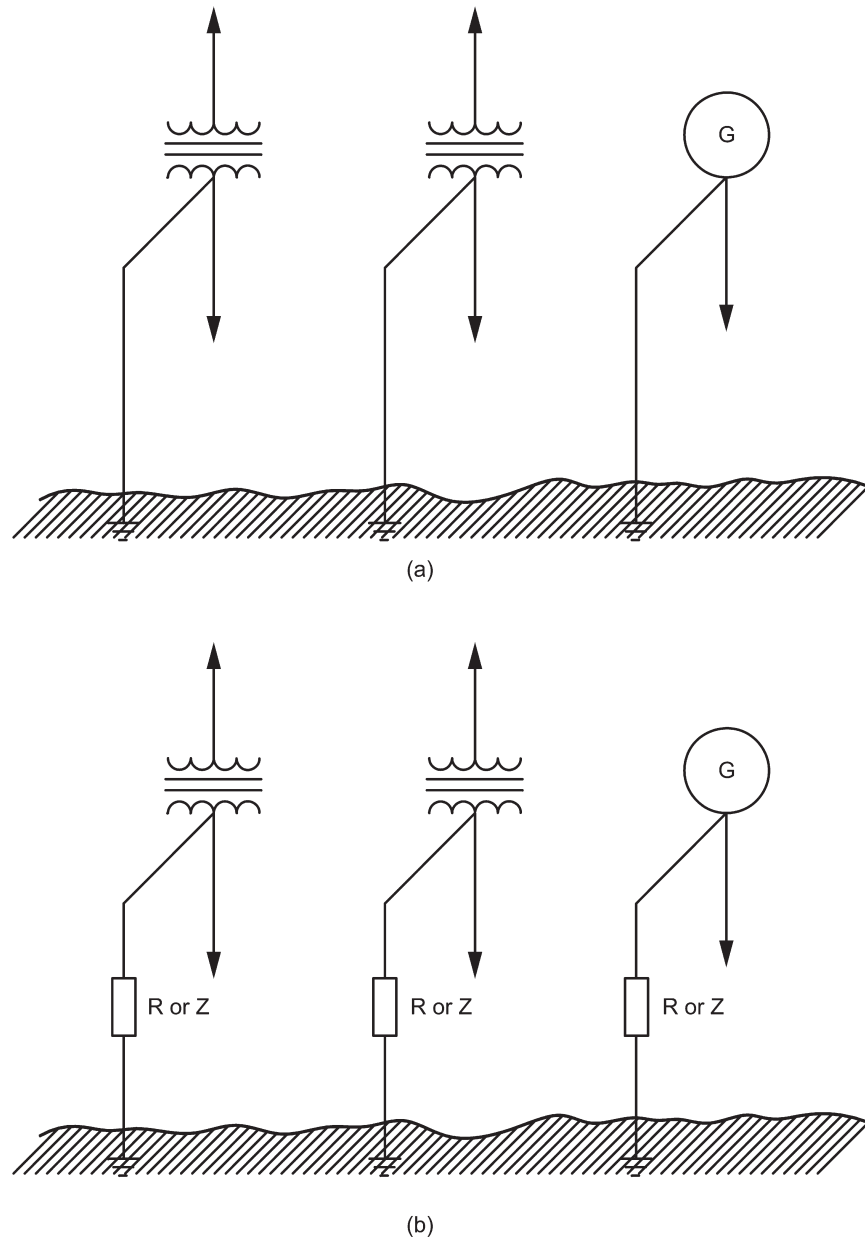


Figure 31—Grounding for systems with multiple power sources (Method 1): a) Solidly grounded, b) R or Z grounded

6.5 Utility to user interface

High-voltage and medium-voltage systems may have multiple neutral grounds where the conductors are overhead outdoors or where they are directly buried with a bare neutral conductor. Given the expansive scope of utility circuits, at the expense of some level of ground (earth) currents, multiple ground points ensure reference to local earth throughout the length of the circuit. To limit stray currents within a user's facility, there is typically a transition from a combined neutral/ground to separate neutral and ground conductors. This transition is illustrated well by the IEC TN-C-S configuration of [Figure 34](#).

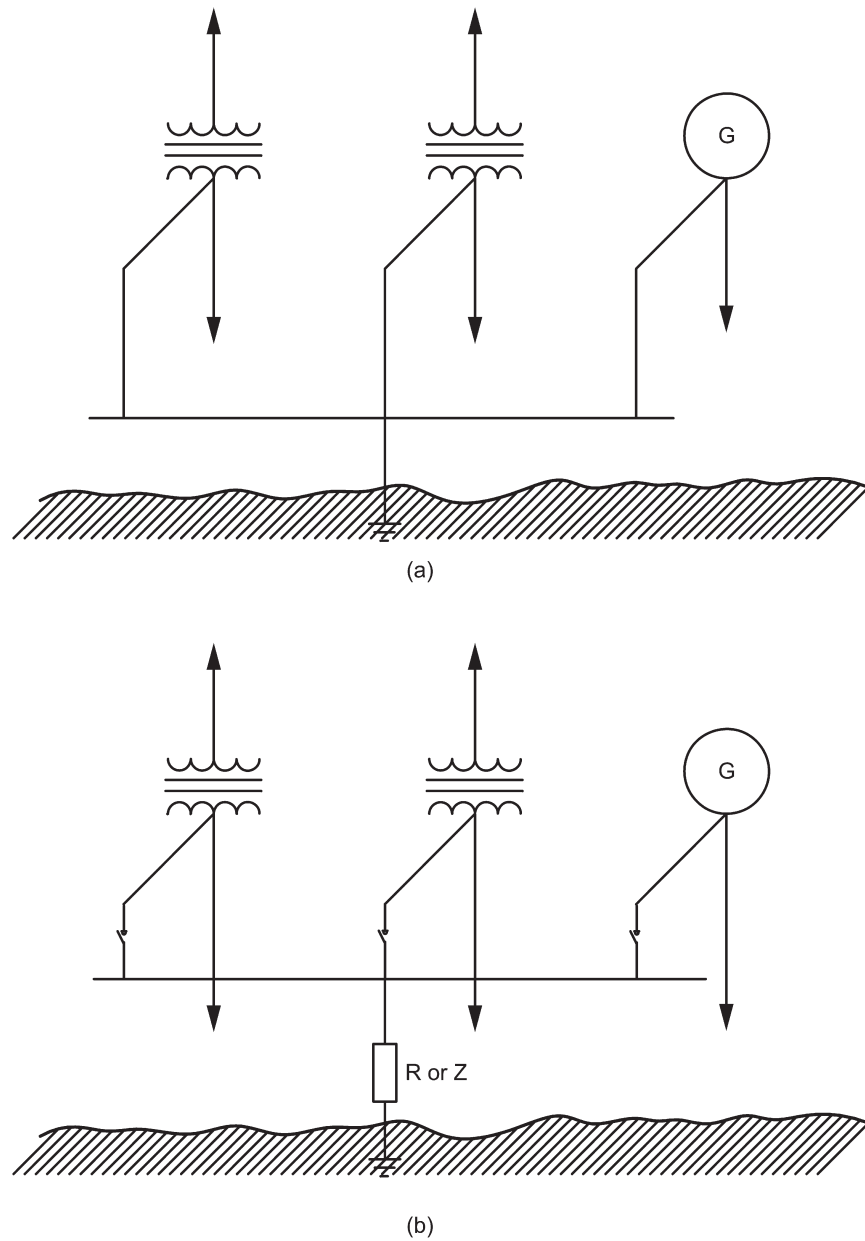


Figure 32—Grounding for systems with multiple power sources (Method 2) a) Solidly grounded, b) R or Z grounded

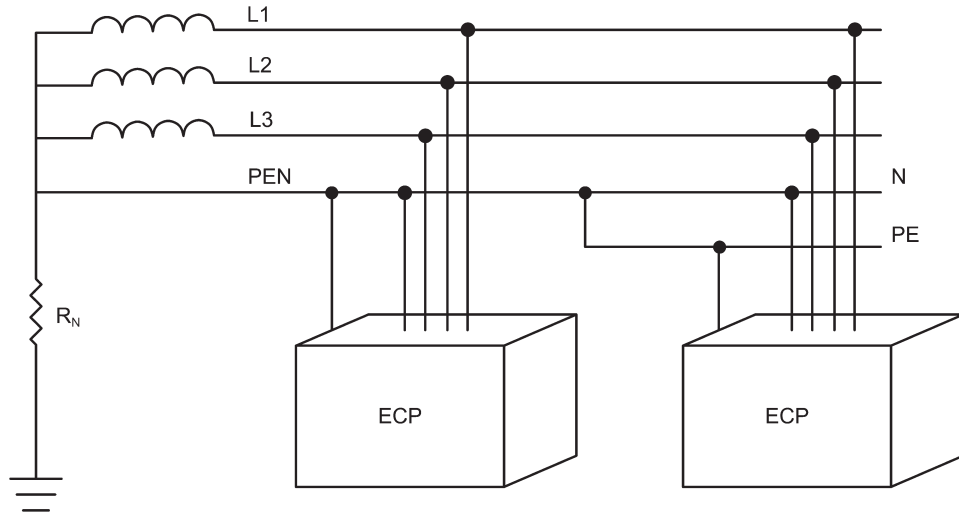


Figure 33—IEC TN-C-S configuration

For medium voltage insulated cable systems, in addition to the change in grounding configuration, there is also a change in typically used cable. The cable of choice for most utilities has a concentric neutral as seen in [Figure 35a](#)). Commercial and industrial facilities typically use cables with the tape shield shown in [Figure 35b](#)). The cable difference is critical during design because the concentric neutral is a circuit conductor that functions as both neutral and ground. A three (3) wire concentric neutral circuit must transition to a four (4) wire plus ground circuit at the user's transition to cable with a taped shield.

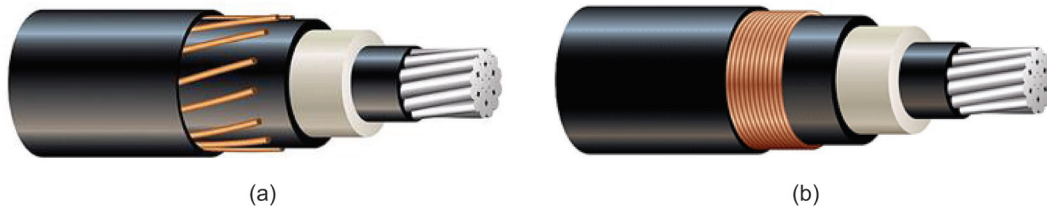


Figure 34—(a) Concentric neutral cable (b) Taped shield cable

In addition to providing the functional properties of both phase and neutral conductors, cables with concentric neutrals can withstand the higher fault currents of solidly grounded systems. These values can be calculated using [Equation \(1\)](#) to enable comparison of short circuit operational capabilities of both concentric neutrals and tape shields for cable sizes presented in [Figure 34](#).

$$t = \frac{A^2 k}{I^2} \quad (1)$$

where:

A is the total cross-sectional area of concentric neutral, tape shield, lead sheath or phase conductor (circular mils)

I is fault current (amperes)

t is duration of fault (seconds)

k is $0.0297 \log \frac{T_2 + 234}{T_1 + 234}$ and

T_2 is final temperature of copper after fault (°C)
 T_1 is initial temperature of copper before fault (°C)

Effective cross-sectional area in cmil, of tape (A) including overlaps of helically applied tape shield is determined by Equation (2).

$$A = 4 \times T_s \times S_D \times \sqrt{\frac{50}{100 - P_L}} \quad (2)$$

where:

T_s is tape thickness (mils)
 S_D is shield diameter (mils)
 P_L is tape overlap (percent)

Typical tape thickness is 5 mils.

While a conductor-to-shield fault will likely damage any cable beyond repair at the point of fault, high currents can damage a taped shield for the length of the cable run. Decreased protective relay trip time is typically required where taped shields are used. Where utility distribution voltages are stepped-down at the point of industrial services, resistance grounding is often applied on the transformer secondary to ensure fault current levels are within operating levels of taped shields.

7. Grounding of industrial and commercial generators

7.1 Industrial and commercial generator characteristics

Generators have several characteristics that are significantly different from transformers, the other common source of power. As compared to the transformer, the generator has little ability to withstand the heating effects or mechanical forces of short circuits. The generator may be required by standards to withstand a less than 10-per-unit short circuit, and the imposition of higher currents is defined as unusual service by the National Electrical Manufacturers Association (NEMA) MG 1, whereas a transformer may be required to withstand a 25-per-unit current. The generator may be capable of withstanding less than 25% of the heating effect of this current as compared to the transformer. If the current is unbalanced, this capability may be reduced to less than 10% of the transformer capability [B27].

Unlike the transformer, the three sequence reactance of a generator are not equal. The zero-sequence reactance has the lowest value, and the positive-sequence reactance varies as a function of time. Thus, a generator will usually have higher initial ground-fault current than a three-phase fault current if the generator has a solidly grounded neutral. According to NEMA, the generator is required to withstand only the three-phase fault current level unless it is otherwise specified (see NEMA MG 1). Also, NEMA states that the negative-sequence current thermal withstand limit is a product of time in seconds and the square of per-unit negative-sequence current (I_2^2t) equaling 40 [B27]. With a solidly grounded neutral, the steady-state ground-fault current will be about eight times that of full-load current, while the steady-state three-phase fault current is three to six times full-load current. Because of the negative-sequence content of the ground-fault current, the generator has less thermal withstand capability than it would for a three-phase fault.

Generators produce slightly non-sinusoidal voltages because of saturation and imperfect winding and flux distribution [B41]. Industrial generators therefore produce odd harmonic voltages, with the third harmonic voltage being as much as 10%. These harmonic voltages can cause heating from circulating currents in a closed loop. This heating is one reason why most industrial generators have their internal windings connected in wye rather than delta. The third harmonic voltages produced in the generator's windings are in phase and additive. This causes third harmonic current to circulate within the delta-connected windings, as shown in

Figure 36. The circulating current creates additional heating within the generator thereby reducing some of its thermal capacity. Generators that operate in a delta connection allow for this additional heating in their design.

Where generator windings are designed with a two-thirds pitch, the third harmonic voltage can be suppressed [B3], but the zero-sequence impedance will be lowered increasing the ground-fault current.

A grounded generator connected to a delta-wye transformer is shown in Figure 37. Any third harmonic voltage, V_3 , produced by the generator would be impressed on the primary of the transformer. Since the third harmonic voltages are in phase, the voltage difference across each winding of the transformer's delta will equal zero and no third harmonic, or multiples of the third harmonic, current can be expected to flow.

Any current flowing as a result of a line-to-ground fault on the secondary side of the transformer will appear, as shown in Figure 38, as a line-to-line fault at the generator output. This type of fault is the most damaging to the generator because of its negative-sequence content. There will be no zero-sequence current flow in the generator even though the generator is grounded. Zero-sequence current will circulate in the delta winding of this transformer.

The physical limitations imposed by generator construction result in less available insulation thickness, with a resulting reduction in voltage-impulse withstand as compared to nonrotating electrical equipment. Special attention should be given to limiting voltage to ground by the grounding of generator neutrals.

Internal ground faults in solidly grounded generators can produce large fault currents. These currents can damage the laminated core, adding significantly to the time and cost of repair. Such currents persist until the generator voltage decays since they are not capable of being interrupted by the generator circuit breaker [B24]. Limiting the magnitude of these currents is the goal of hybrid grounding presented in Figure 16.

NOTE—One per unit is equal to generator-rated current.

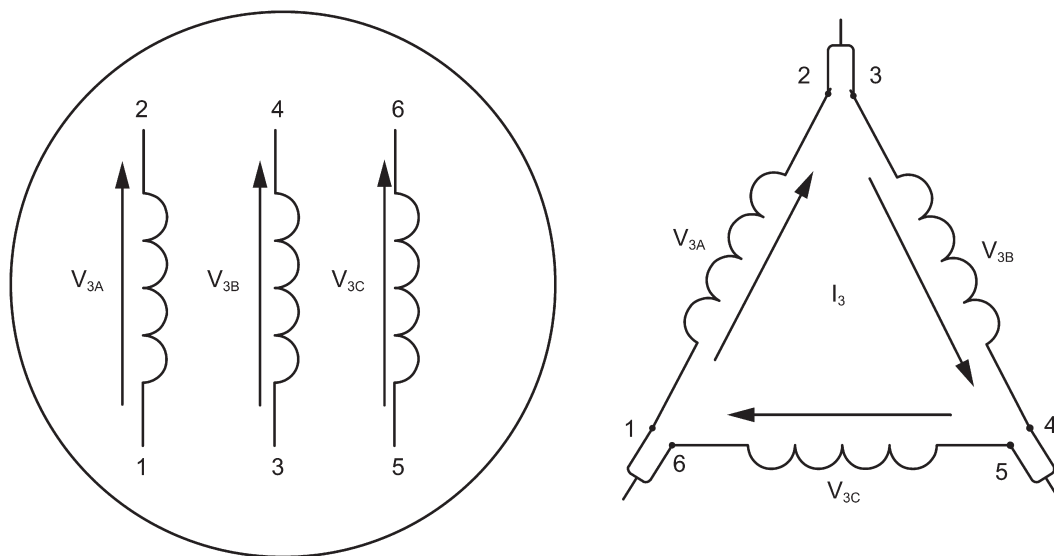


Figure 35—Circulation of third harmonic current in a delta connected generator

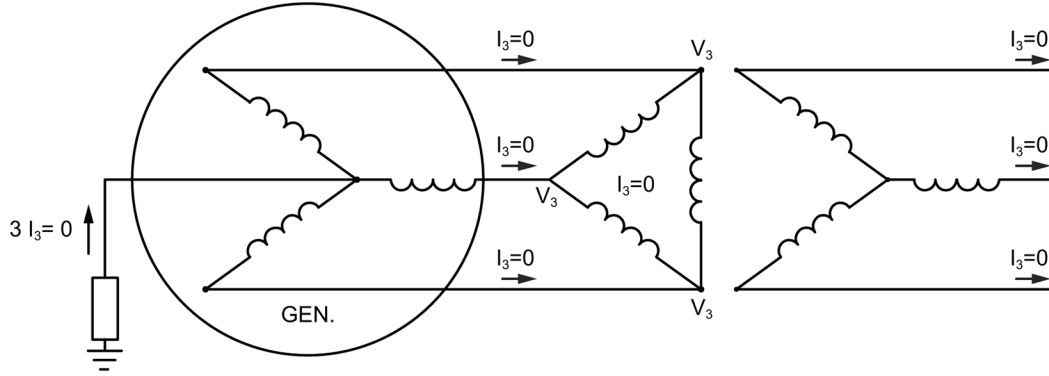


Figure 36—Third harmonic current (no zero-sequence loop)

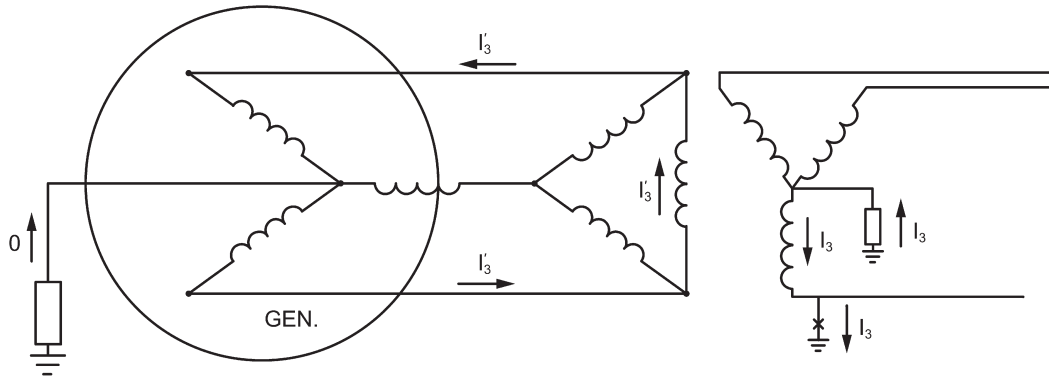


Figure 37—Single unparalleled generator

7.2 Single-unparalleled generator

A single-unparalleled generator may offer the most options for grounding. The distribution system may be particularly designed for flexibility in applying grounding by having only three-wire loads connected directly to the generator or even having only a single transformer connected to the generator (unit bank). Thus the design may employ high-resistance grounding to minimize damage from internal ground faults, or low-resistance grounding if needed to operate selective ground relays. In either case, the ground-current level should be substantially less than the phase-current fault levels.

The generator may also be applied to a four-wire load without transformation. If the generator is rated for solidly grounded service, the neutral may be connected directly to the grounded circuit conductor. If a standard generator is used, a reactor should be connected between neutral and the grounded circuit conductor so as to limit the momentary ground-fault current to no more than the momentary three-phase fault current ([B4] and NEMA MG 1). When $3i_0 = i''_d$ the value of this neutral reactor, X_N , should be as shown in Equation (3):

$$X_N = \frac{(2X_d'' - X_2 - X_0)}{3} \quad (3)$$

where:

$3i_0$ is the ground-fault current and equals:

$$\frac{3 \cdot V_{in}}{(X_d'' + X_2 + X_0 + 3 \cdot X_n)} \quad (4)$$

where

i_d'' is the three-phase subtransient fault current, which is $\frac{V_{in}}{X_d''}$

X_d'' is the generator subtransient reactance

X_2 is the generator negative-sequence reactance

X_0 is the generator zero-sequence reactance

V_{in} is the phase to neutral voltage

Note that a resistor should not be used for this purpose since its impedance is in quadrature with the machine reactance and thus would require a much larger value of resistance than reactance. This resistance would incur large losses from the flow of either fault or load current. The zero-sequence load current would also produce an objectionable voltage drop since the load is primarily resistive.

On the other hand, the neutral reactor will cause little voltage drop to be produced by in-phase zero-sequence load current. The total zero-sequence current will be a small value because the generator has limited unbalanced current capacity. The continuous negative-sequence current capability of generators covered in ANSI C50 standards is 8% or 10%. For salient-pole generators covered under NEMA MG 1, the limit is 10% at full load. The use of the reactor between the generator neutral and the neutral circuit conductor does not affect the need for the neutral circuit conductor being solidly grounded.

If generators are solidly grounded, the system's circuit breaker duty must be calculated at the higher ground fault duty.

If the wye side of a delta-wye transformer is connected to a generator that is configured for four-wire service, the generator should be designed with a two-thirds pitch winding. This transformer will act as a short circuit to third harmonic currents, and without cancellation of third harmonic voltage, the resultant current may adversely affect ground-fault relaying and generator capacity.

7.3 Paralleled generators in an isolated system

This subclause covers only those generators that are paralleled to other generators on the same bus. Generators paralleled through transformers would be considered as paralleled to a separate source [B35].

7.3.1 Circulating harmonic current

There is a possibility of circulation of third harmonic current between solidly grounded generators if any of the generators do not have two-thirds pitch windings. For generators of other than two-thirds pitch of identical design, there will be little circulation of third harmonic current while the generators are being operated at identical power and reactive current outputs. If non two-thirds pitch generators are not of identical design, third harmonic circulating current becomes an issue as is also the case if identical non two-thirds pitch generators are operated with unequal loading.

This issue is demonstrated in Figure 39, where two generators are shown solidly connected to a neutral bus [B24]. Due to differing electrical parameters and construction details, each generator produces a different amount of third harmonic voltage, e_{31} and e_{23} , at its terminals. As a result, a third harmonic current circulates between the generators. The magnitude of this current depends on the third harmonic loop voltage, e_3 , and the third harmonic loop impedance, Z . Since the generators are solidly connected to the neutral bus, the third harmonic loop impedance can be small. The resulting circulating current produces additional heat in each

generator. More important, the zero-sequence third harmonic current circulating through the loop may pick up ground relays causing false tripping of the generator circuit breakers [B24].

While producing no third harmonics, generators with two-thirds pitch windings have the minimum impedance to the flow of third harmonic currents generated elsewhere due to their low zero-sequence impedance.

High-resistance grounding of the generators will adequately limit these harmonic currents. Thus, it is advantageous to use high-resistance grounding on the generators, as shown in Figure 40, even if there are load feeders directly connected to the generator bus, and to use low-resistance bus grounding to provide selective relaying on the load feeders. Low-resistance grounding of the generators at values not exceeding 25% of generator rating will normally suppress third harmonic current to adequate values even with dissimilar generators, but the variable ground-fault current available with multiple generators may pose a relay-coordination problem. While resistance grounded generators are unable to directly support line-to-neutral loads, such loads are easily accommodated by addition of a delta-wye isolation transformer.

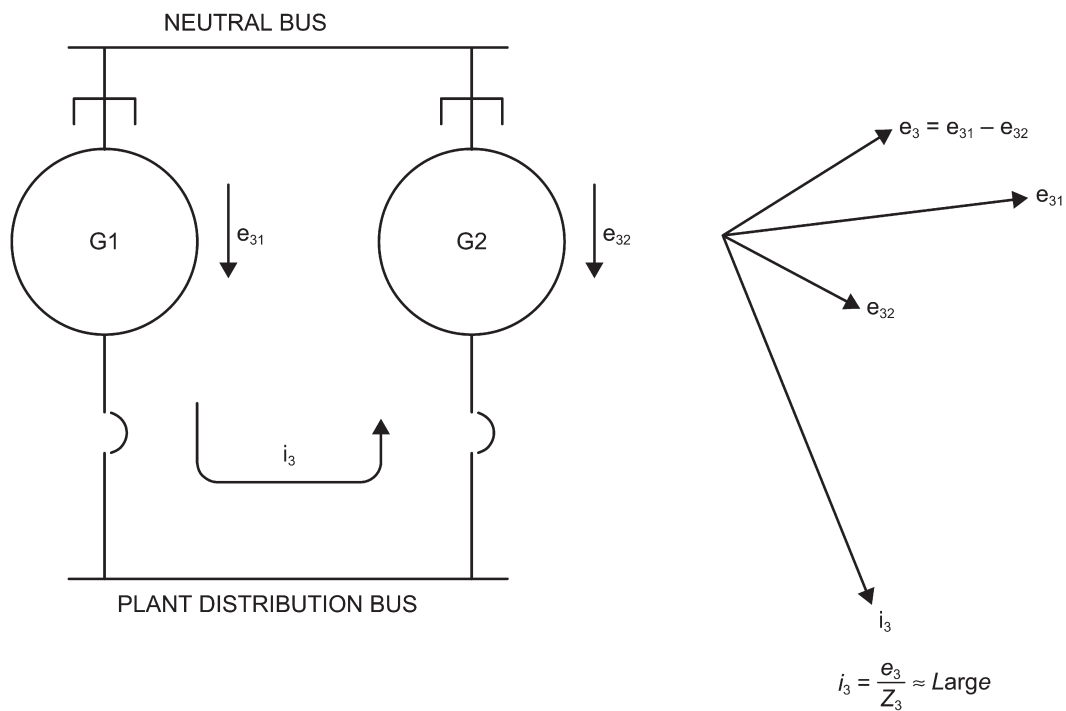


Figure 38—Two parallel generators solidly connected to a neutral bus

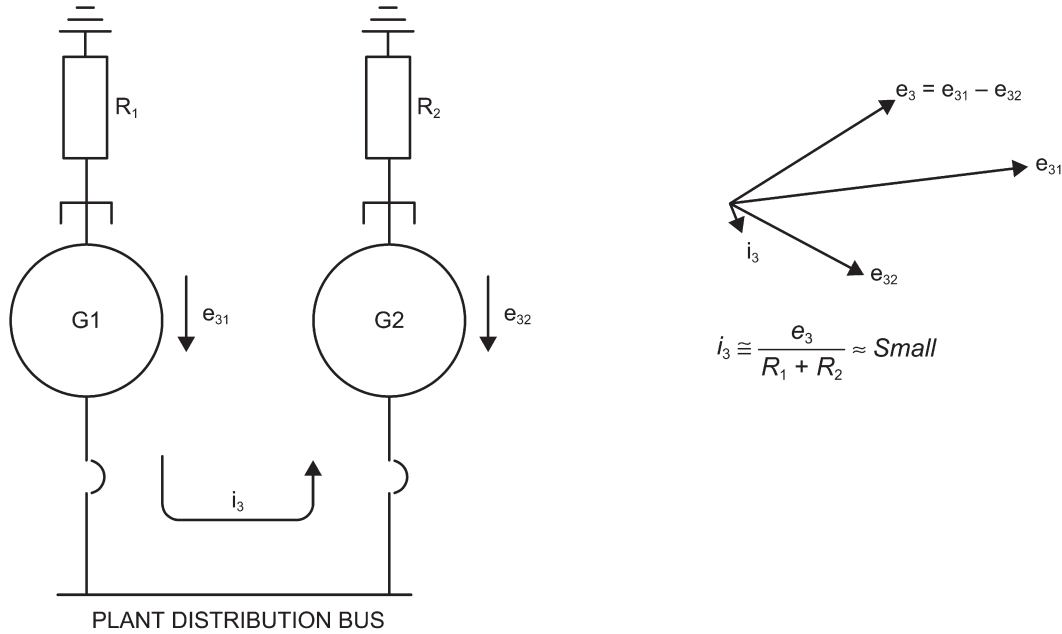


Figure 39—Two parallel generators with grounding resistors

7.3.2 Ground fault limitations

NEMA MG 1 places a requirement on the design of synchronous generators that windings shall be braced to withstand the mechanical forces resulting from a bolted three-phase short circuit at the machine terminals. Generator phase currents to ground can actually exceed these three-phase values causing possible machine damage [B41]. This condition can be illustrated by Equation (5) considering a generator with typical per unit impedances of:

$$X_1 = X_2 = 0.14 pu, X_0 = 0.08 pu \quad (5)$$

where X_1 , X_2 , and X_0 are the positive, negative, and zero-sequence reactance, respectively. The three-phase fault current, I_{3ph} , at the generator terminals, as a function of the line to neutral voltage is shown in Equation (6):

$$I_{3ph} = \frac{E_{LN}}{X_1} = \frac{1}{0.14} = 7.14 pu \quad (6)$$

If the generator neutral is solidly grounded, the line-to-ground-fault current, I_{SLG} , at its terminals, as given by Equation (7):

$$I_{SLG} = \frac{3E_{LN}}{(X_1 + X_2 + X_0)} = \frac{3}{(0.14 + 0.14 + 0.08)} = 8.33 pu \quad (7)$$

The ground-fault current is therefore $8.33/7.14 = 1.17$ times the required generator design capability. Since ground faults are more likely to occur than phase faults, they pose a greater potential threat to the system.

If two generators are connected in parallel as shown in Figure 41 and only one is solidly grounded, then the ground-fault current increases to 1.91 times three-phase fault current of one generator. The current in the

faulted phase of the grounded generator further increases to 1.27 times the required design value. Both can be seen by considering the phase A current at the fault, as shown in Equation (8):

$$I_1 = I_2 = I_0 = \frac{1}{(0.07 + 0.07 + 0.08)} = 4.545 \text{ pu} \quad (8)$$

$$I_a = I_1 + I_2 + I_0 = 13.63 \text{ pu}$$

where I_1 , I_2 , and I_0 are the positive, negative, and zero-sequence components of the fault current.

In the grounded generator [see Equation (9)]:

$$I_0 = 4.545 \text{ pu} \quad (9)$$

$$I_1 = I_2 = \frac{4.545}{2} \text{ pu}$$

$$I_a = 4.545 + 2 \left(\frac{4.545}{2} \right) = 9.09 \text{ pu}$$

and the ground-fault current is $13.63/7.14 = 1.91$ times the calculated three-phase fault current of one generator. The phase A current in the grounded generator is now $9.09/7.14 = 1.27$ times the three-phase faulted level of one generator.

The preceding example provides reasons for not solidly grounding generator neutrals. Where the neutrals are to be grounded, impedance should be added.

Where multiple generators are solidly grounded but have switches in the neutral, there has sometimes been the practice of grounding only one of the generators in parallel to limit ground-fault current duty or circulating third harmonic current. This will increase the fault-current in the grounded generator above that for which it would be customarily rated. A chart showing this difference appears in [B15]. The ability to switch neutrals also invites operational errors that could affect integrity of grounding. Ungrounded operation during switching allows overvoltage on four-wire loads leading to possible equipment damage.

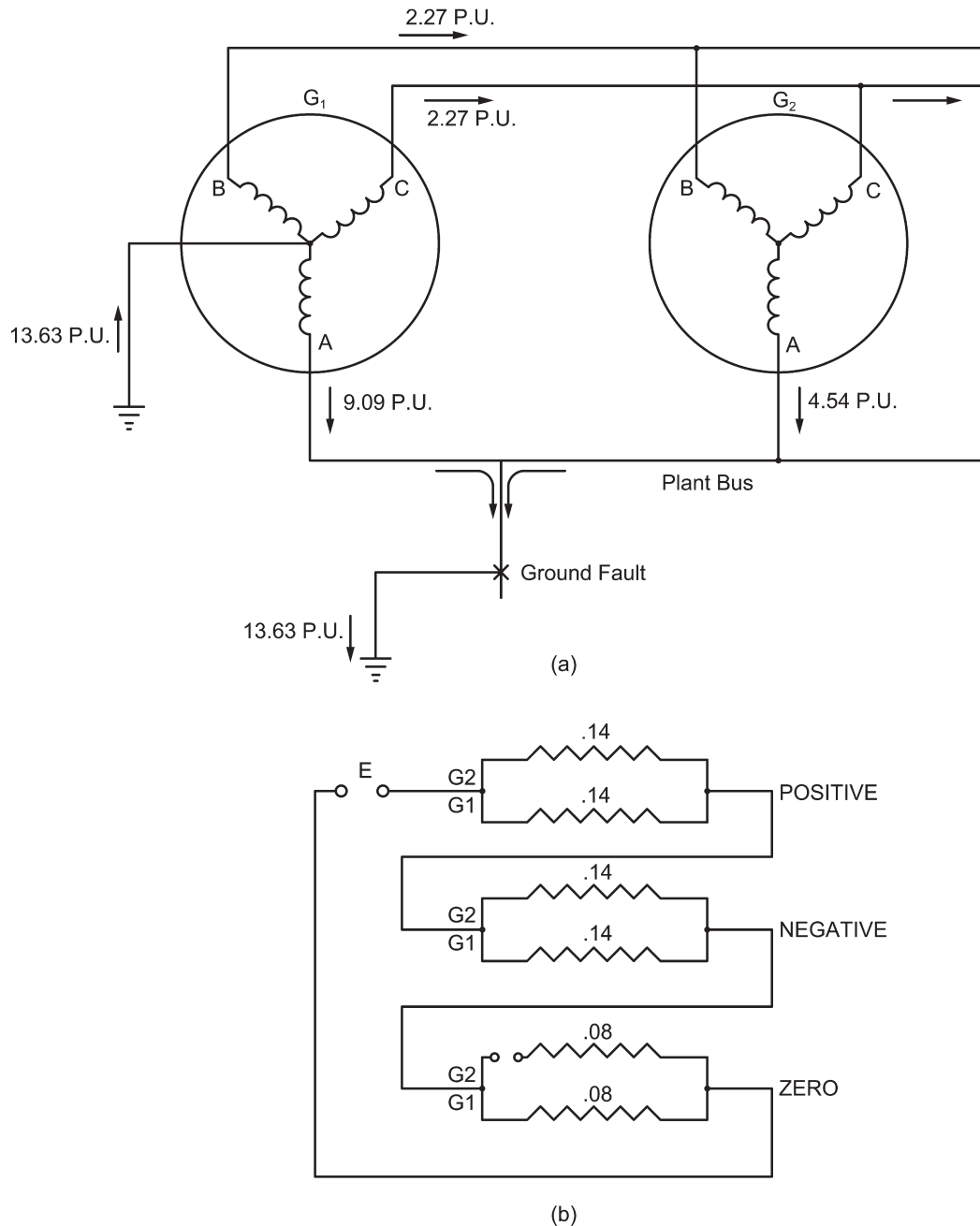


Figure 40—Ground fault on a system with two parallel generators

7.4 Generators as unparalleled alternate sources

This category covers emergency and standby generators that are connected to the loads by transfer switches, which precludes paralleling with the normal source. With three-wire systems, the generators would be considered a separately derived source since there would be no continuous connection through a system neutral.

Where four-wire systems are involved, neutral currents can flow between the system and generator neutral grounding points if a three-pole transfer switch is used. Whether or not the neutral is grounded at the generator

as well as at the normal service, ground-fault relaying errors can occur. Where service ground fault protection is required, as in services above 1000 A for 480 V and 600 V systems, a four pole transfer switch is required.

Neutral grounding at a generator is typically not required when it has a common neutral with the grounded utility service neutral conductor. This scheme still provides an alternate path for neutral current. Also, repair or testing of system grounding may involve disconnection from ground of the neutral conductor. Should there be only one connection and the generator is operating, there is the hazard that workers performing such repair, or tests, may not be aware that the generator is operating. This type of hazard can be avoided by the separation of normal and generator grounding which provides merit for use of a four-pole transfer switch even where ground fault protection is not an issue.

7.5 Generators paralleled with other sources

This category describes generators connected to transformers that are, or can be, connected to other power sources. While the primary consideration is the generator grounding, decisions can be affected by the necessity of providing the desired grounding on the other side of the transformer while other generating sources may be disconnected.

The use of a delta-wye transformer, as shown in [Figure 42](#), with the wye facing the generator offers the advantage of providing neutral grounding, solid or impedance, to the generator-fed bus when the generator is not connected. The use of this type of transformer has the disadvantage of not offering grounding to the system connected to the delta side of the transformer. In the event that the transformer is removed from service, an alternate ground source would be needed. This alternate grounding source does present a hazard if both the transformer and generator neutrals are solidly grounded.

The wye winding with a delta primary is a short circuit to any third harmonic current produced by the generator. The ground-fault duty on the bus will be greater than the arithmetical sum of the ground-fault currents supplied by the transformer and generator when each is connected to the bus independently. The ground-fault current in the generator will exceed that which would occur when the generator is not paralleled. The fault currents must be calculated using symmetrical component techniques rather than simply using the sum of the admittances of the transformer and generator sources. A generator rated for grounded service is normally rated only for the ground-fault current flowing when not paralleled.

A generator neutral reactor can be used to limit the generator-fault duty to an acceptable value as calculated but may not limit any generated third harmonic current to an acceptable value. Thus, suppression of third harmonic may be necessary to facilitate adequate ground-fault relaying.

If the delta of a delta-wye transformer is connected to the generator bus, as shown in [Figure 43](#), neutral grounding is available on the wye side of the transformer. However, the generator bus will be ungrounded until such time as the generator is grounded or independent bus grounding is employed. Some type of grounding transformer (wye-delta or zigzag transformer) can be used to produce either effective or impedance grounding of the bus. If a grounding transformer is connected to the bus, the generator may be high-resistance grounded.

These methods of grounding are also described in IEEE Std C37.101™, which covers generator ground-fault protection as well. It should be noted that this standard was developed primarily for utility generators and does not contain some of the considerations for industrial applications.

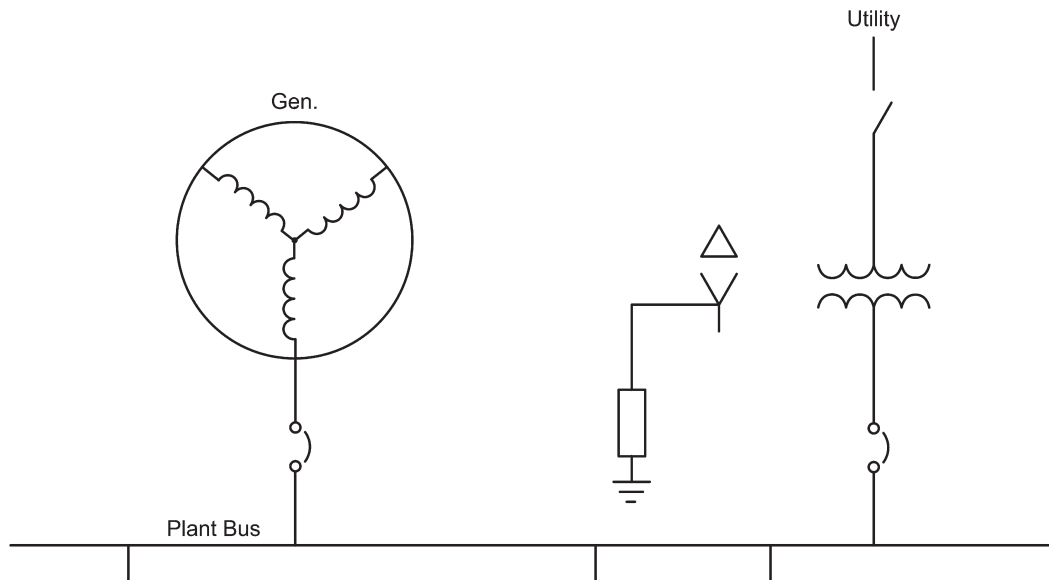


Figure 41—Generator in parallel with a transformer

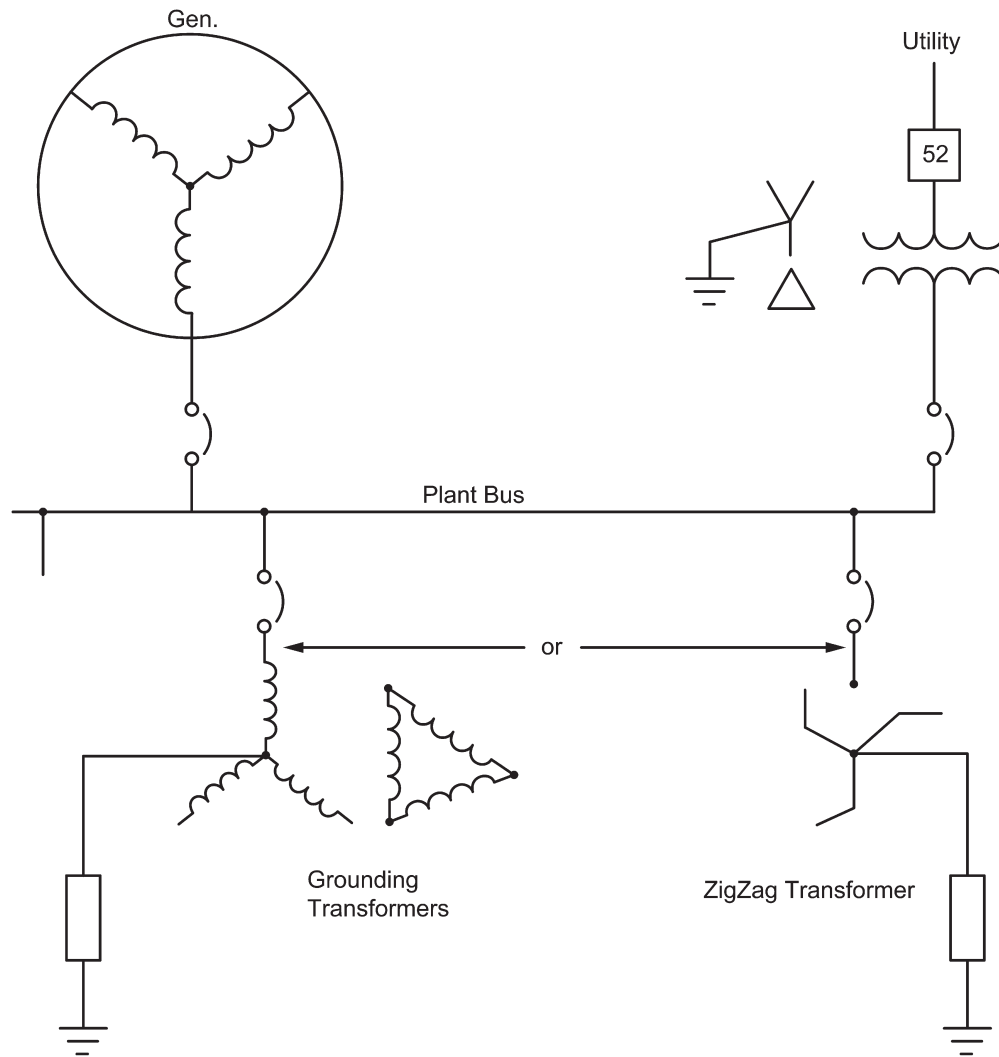


Figure 42—Grounding transformers in a distribution system

8. Autotransformers

Occasionally autotransformers are used to modify voltage, usually to reduce transformer cost, or perhaps to avoid creating a new grounding system. Unless the system grounding is suitable for the use of an autotransformer and the autotransformer is properly applied, its use may seriously reduce grounding and ground relaying effectiveness and expose equipment to a voltage-to-ground level higher than that for which it is designed.

The three-phase wye autotransformer with no delta tertiary has extremely high zero-sequence impedance if no connection is made to its neutral. Figure 44 shows that a ground fault at A' will cause the source line-to-ground voltage to be imposed across the A-A' section of the autotransformer. Should that section of the winding be able to support this voltage, then the voltage to ground at N, the neutral of the autotransformer, would rise in proportion to the turns ratio of A'-N to A-A', and B' and C' would have voltages to ground higher than B and C, the high-voltage level. The secondary line-to-line voltage can also be increased.

In normal practice, winding A-A' would not support the full voltage, but would instead saturate, thus passing a certain amount of zero-sequence current. In the process, this type of installation will create high-frequency

components of voltage, at which frequency the winding can support a voltage proportional to that frequency. Thus, a very high voltage to ground could still exist at N.

Even if the secondary of the autotransformer is the higher voltage, it will still be overvolted by a secondary line-to-ground fault. This reference also points out that overvoltages can also be caused by transient surges, such as from switching or lightning, being impressed across the section of winding between the primary and secondary connections.

Figure 44 shows that when a source to a step-down autotransformer is impedance grounded, a ground on the source side of the autotransformer can cause the voltage from B' and C' to ground to approach the line-to-line voltage of the source. If the autotransformer steps up the voltage, the voltage to ground on the lower voltage system will lie between that shown in Figure 45 and what might be achieved in Figure 46, depending upon the relation of the grounding impedance to the exciting impedance of the autotransformer.

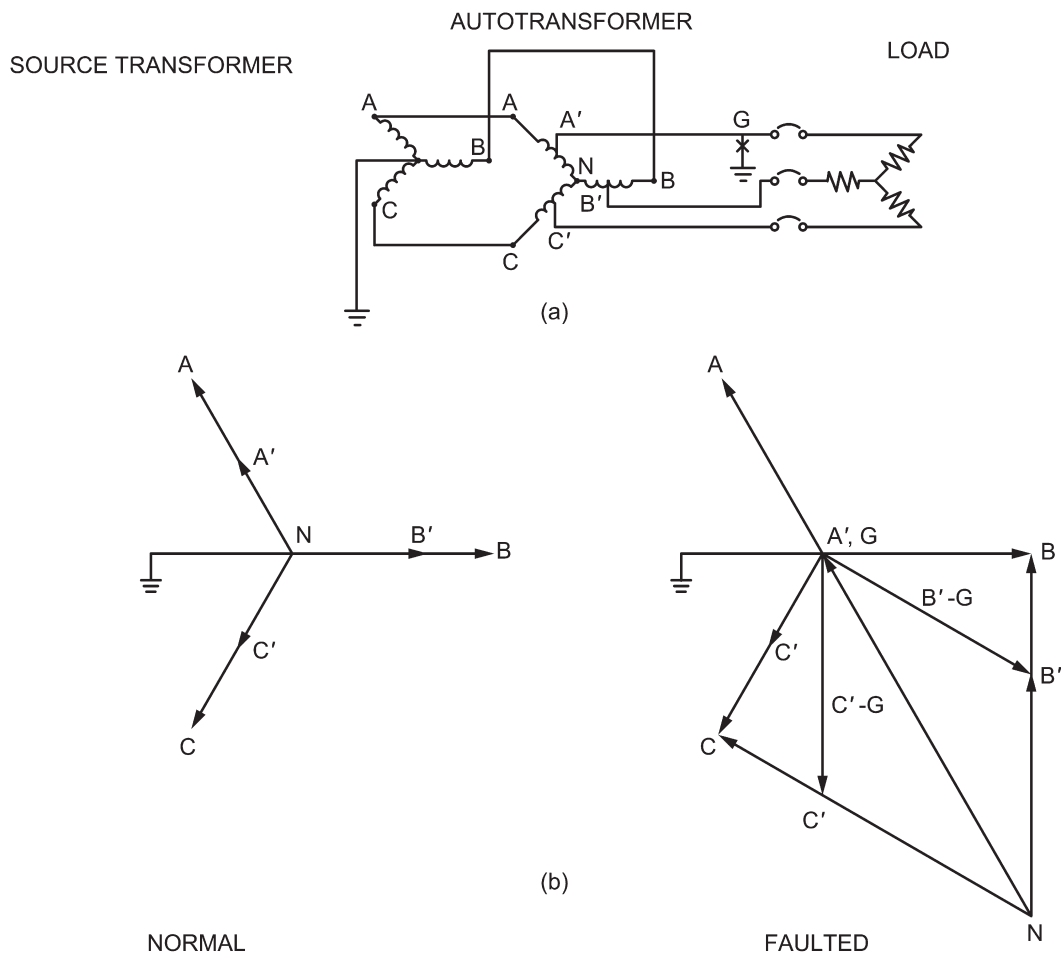


Figure 43—a) Ungrounded wye step down autotransformer with load fault, b) Normal and faulted voltage phasors

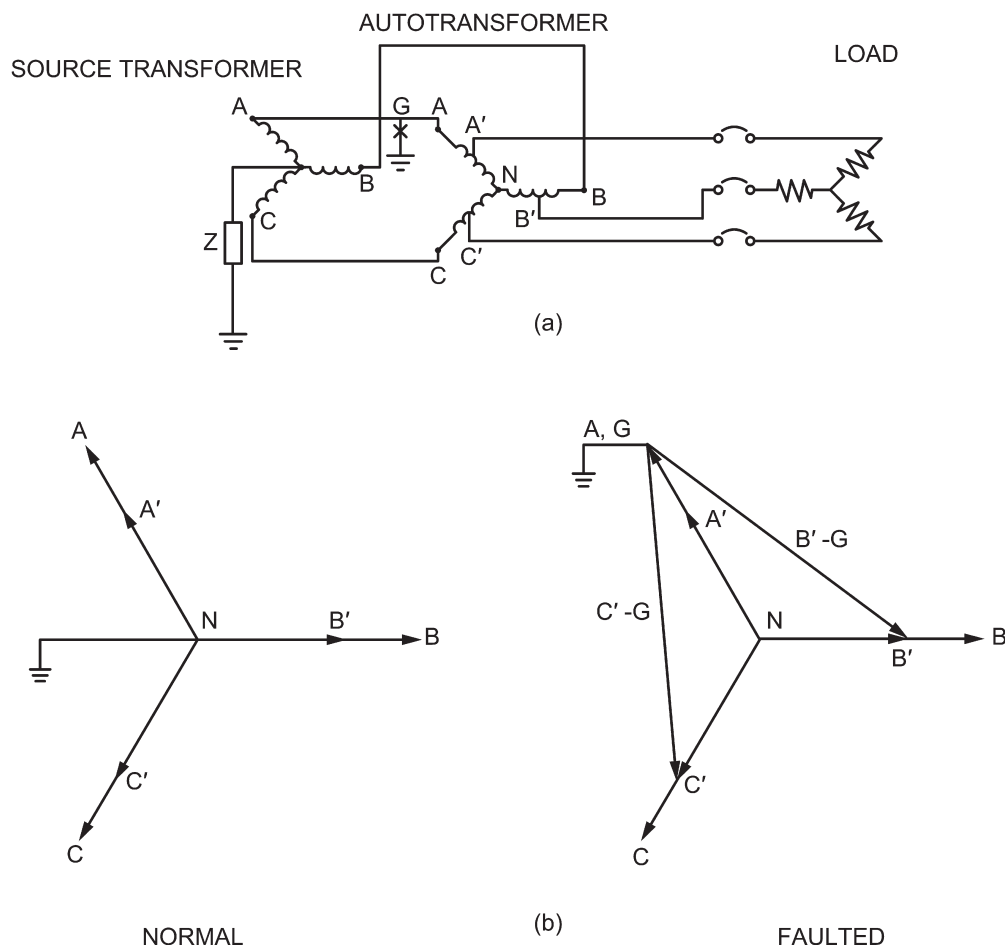


Figure 44—a) Ungrounded wye step down autotransformer with primary fault, b) Normal and faulted voltage phasors

Figure 47 shows that delta autotransformers do not offer a reduction in voltage to ground on the lower voltage system commensurate with the reduction in phase voltage, thus reducing the cost benefit of choosing the autotransformer rather than a full transformer. The open-delta version offers no reduction in maximum voltage to ground, but does result in an unbalanced voltage to ground that might be undesirable. In neither case do ground faults cause increased voltages to appear across the transformer windings, and line-to-ground voltage at either voltage will not exceed the higher line-to-line voltage. Should a full transformer be used in either case, reducing the class of insulation in the lower voltage system might be possible. Like most solidly grounded systems, a large ground-fault current will occur, limited primarily by transformer impedances. The actual voltage drops across the two transformers will have complex relationships depending upon the relative ratings and saturation characteristics of the two transformers. These voltage drops are not necessarily in phase.

Figure 48 shows the correct configuration for using an autotransformer. There must be an effective connection between the neutral of the autotransformer and the neutral of the source transformer for flow of zero-sequence current. In an industrial installation, the connection must be made by extending the neutral of the source transformer. No neutral to ground connection should be made at the autotransformer. A circuit supplied by an autotransformer does not meet the criteria of a separately derived system.

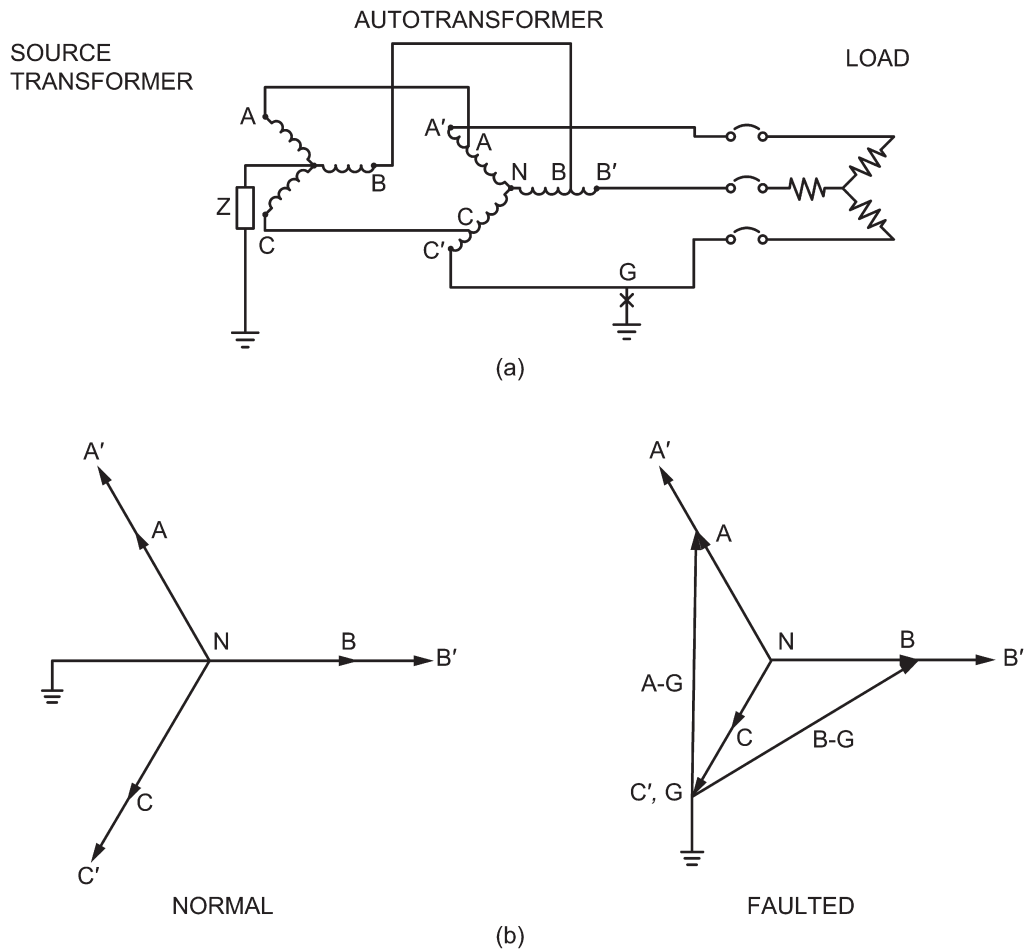


Figure 45—a) Ungrounded wye step-up autotransformer with load fault, b) Normal and faulted voltage phasors

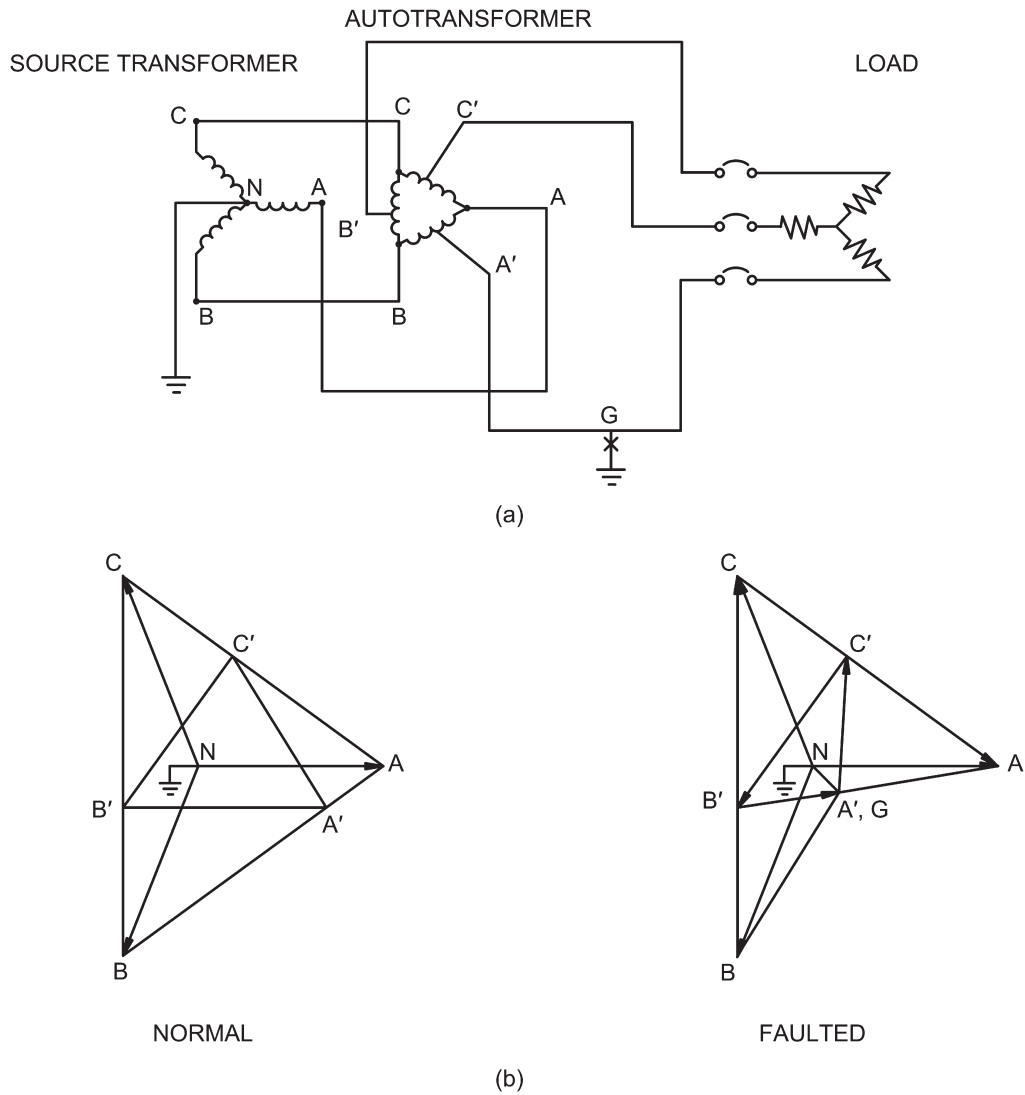


Figure 46—**a)** Delta autotransformer with load fault **b)** Normal and faulted voltage phasors

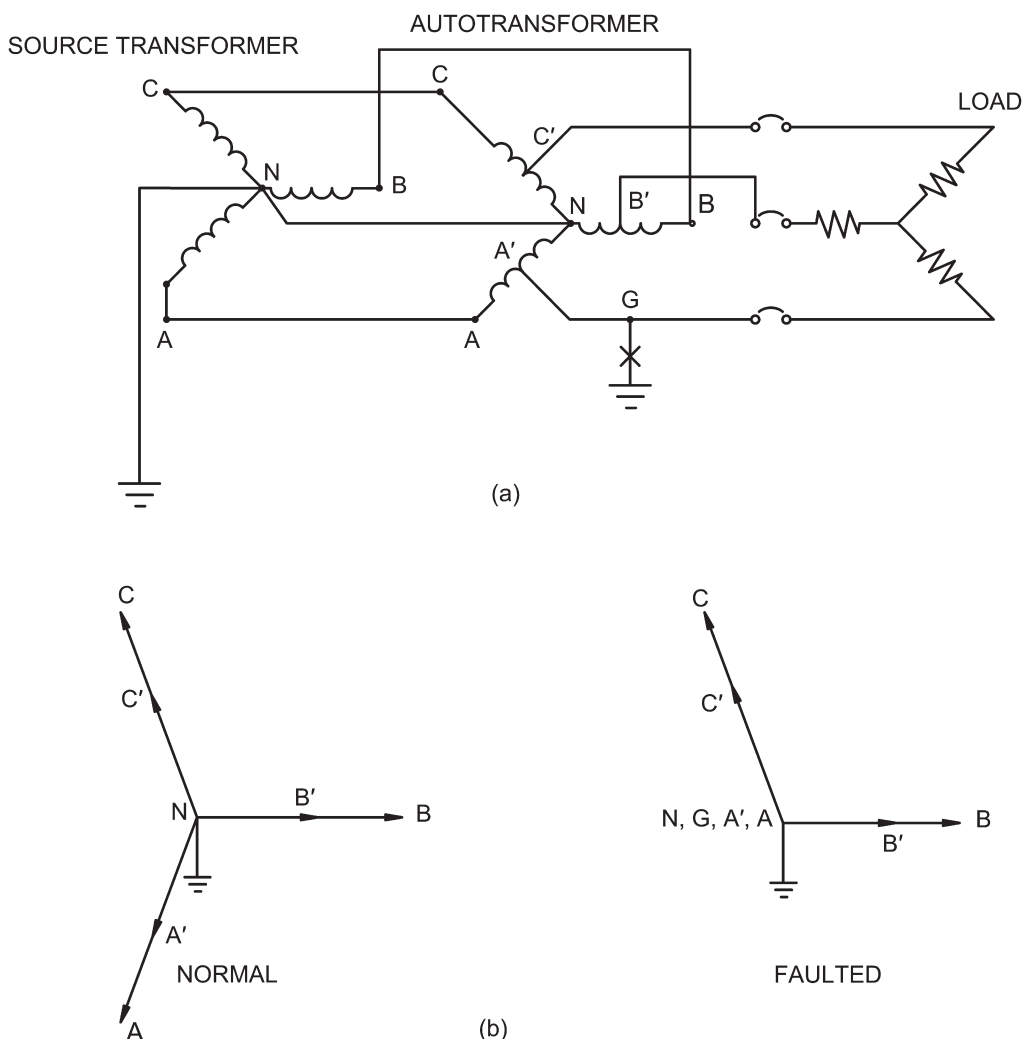


Figure 47—a) Wye autotransformer with grounded neutral, four-wire connection, b) Normal and faulted voltage phasors

9. System grounding for uninterruptible power systems

9.1 General

As with any electrical system, correct grounding of uninterruptible power supplies (UPS) is essential to the overall safety and performance of the system. In particular, personnel safety, equipment protection, and electronic performance can all be jeopardized by incorrect or ineffective grounding.

UPS units come in a variety of configurations. For UPS units with an integral output isolation transformer, the UPS ac output is electrically isolated from the UPS ac input. However, most practical UPS systems also include one or more bypass arrangements, which, depending on the particular arrangement, makes the UPS system either a separately derived system or not. Some of the potential arrangements are shown in [Figure 49](#), [Figure 50](#), and [Figure 51](#). In these figures, protective conductors are shown supplementing the conduit grounding of the enclosures as is recommended practice. Battery cabinets are shown, but racks of batteries may also be used with UPS systems. The UPSs are shown as single units but may consist of one or more parallel-connected modules, particularly for larger capacity or redundancy. More elaborate schemes than presented in the three examples may be encountered. Additional wraparound maintenance bypass switching

schemes are often added to the basic UPS configurations to facilitate maintenance of the UPS unit while continuing to supply power to the load.

9.2 Separately derived UPS system

Figure 49 depicts a conventional static UPS unit whose ac (inverter) output is electrically isolated from the main ac (rectifier) input. The static bypass input is supplied with a three-wire-plus-ground feed from a solidly grounded power system. There will be two configurations in this scheme. In normal configuration, the UPS ac output is a separately derived system. UPS units without an integral output isolation transformer do not provide electrical (galvanic) isolation between the UPS ac output and its ac input and should not be treated as a separately derived system. Any ground-fault current on the output of the transformerless UPS returns to the source of the ac input and not the UPS inverter output. Transformerless UPS units with 4-wire ac output should be used with a 4-wire ac bypass input to properly reference the transformerless UPS system. As such, the UPS ac output is grounded in accordance with requirements for separately derived systems. The UPS output neutral is bonded to the protective conductor, and a grounding electrode conductor (GEC) is connected to the nearest effective grounding electrode. If the UPS output neutral is not correctly connected to the GEC, the UPS output will not be properly referenced to ground with the resulting uncontrolled voltages to ground. In bypass configuration, the output of the UPS is not a separately derived source.

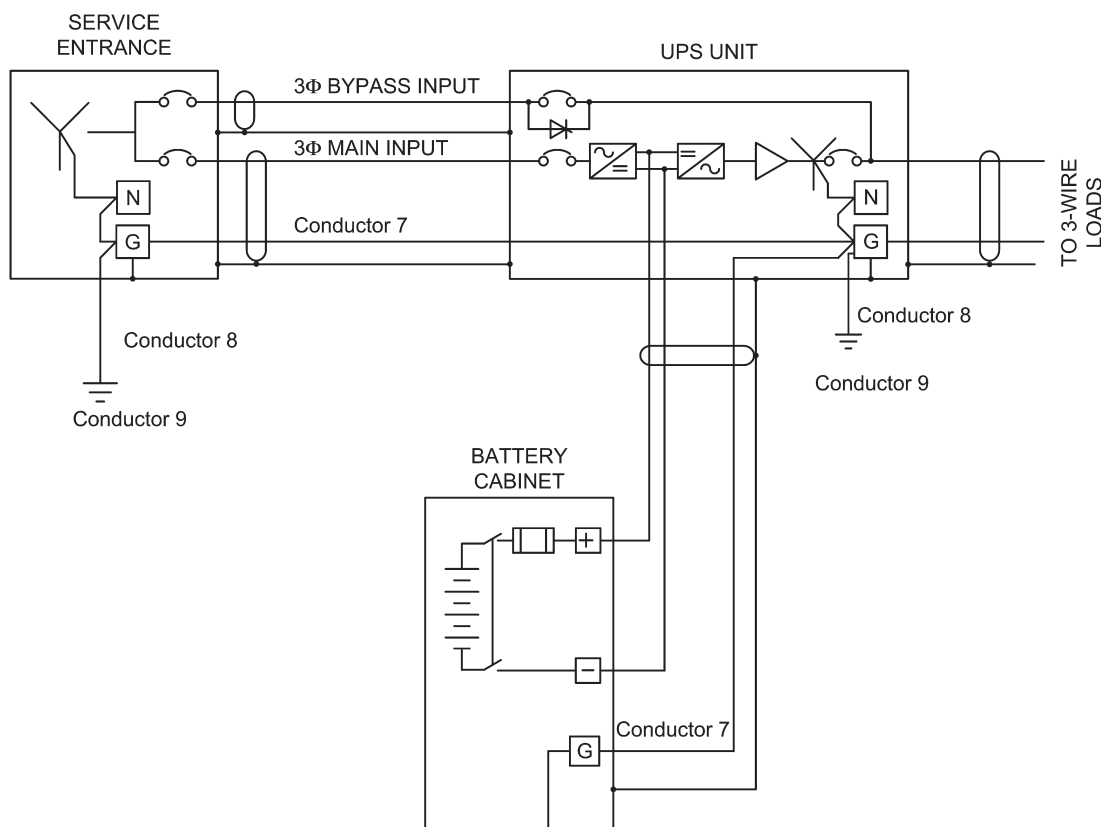


Figure 48—Separately derived UPS system

9.3 Non-separately derived UPS system

Figure 50 depicts the same conventional static UPS unit shown in Figure 49 except that the bypass input is supplied with a four-wire-plus-ground feed from a solidly grounded power system. This configuration is

often encountered when line-to-neutral loads are served directly from the UPS. In this configuration, the UPS output neutral is solidly connected to the grounded bypass neutral. Most UPS units do not switch the bypass and output neutral when the phases are switched. Therefore, the UPS output is not a separately derived system but rather a solidly grounded interconnected system. As such, the UPS neutral may not be connected to the protective conductor or a GEC. If the UPS output were mistakenly connected to the protective conductor or GEC, the bypass input power system would be grounded at more than one point. This has the adverse consequence of allowing normal neutral currents to flow on the grounding system that can cause electronic equipment and ground fault protection to malfunction.

When the UPS is configured as a non-separately derived system (a solidly grounded interconnected system), a ground fault on the output of the UPS must return to the UPS neutral by way of the upstream system (service entrance) neutral-to-ground bond and, as such, may trip upstream ground fault protection devices.

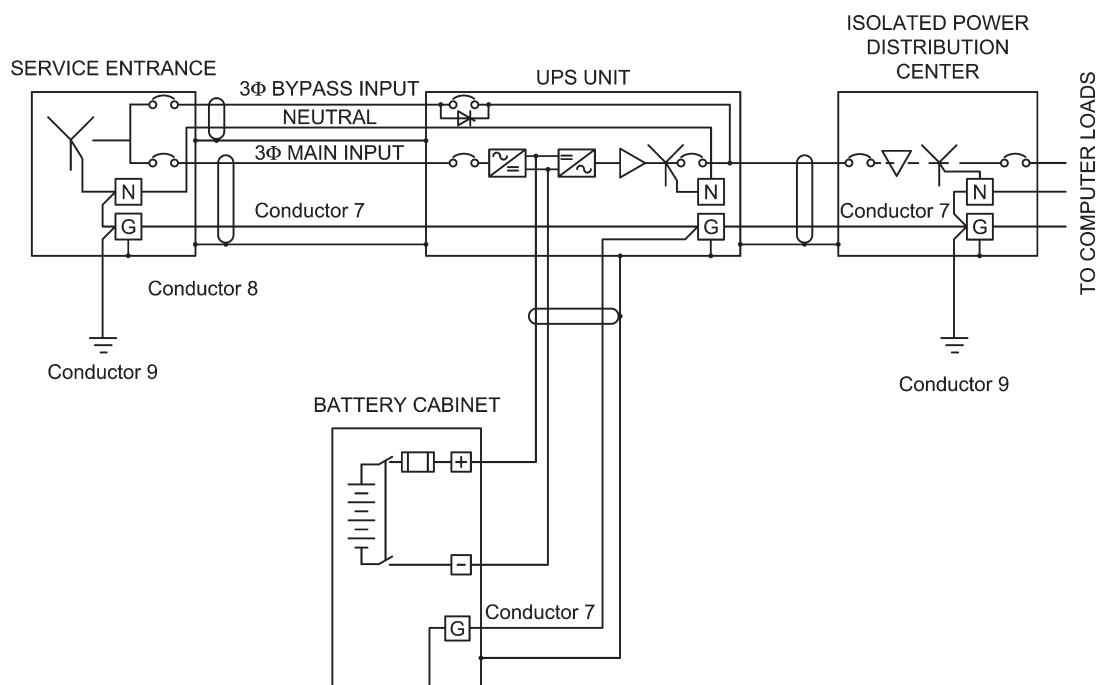


Figure 49—Non-separately derived UPS system

9.4 Separately derived UPS system serving four-wire loads

Figure 51 depicts the same conventional static UPS unit serving four-wire loads as shown in Figure 50 except that the UPS bypass input is supplied from a bypass transformer that isolates the four-wire-plus ground bypass feed to the UPS and allows the UPS system to be separately derived. This configuration is useful to provide power source grounding (neutral-to-ground bond) close to the loads, which is recommended for electronic loads. The neutral-to-ground bond can be located at the UPS output or at the bypass transformer, but not both.

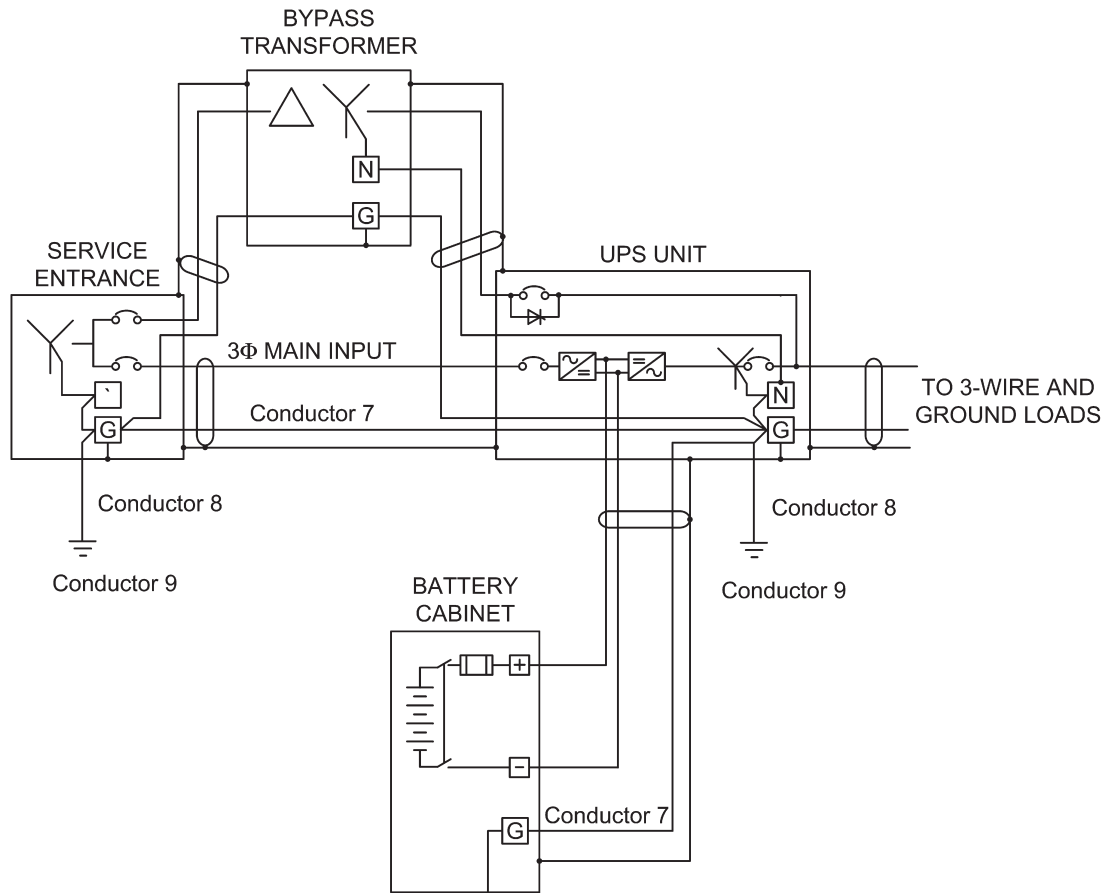


Figure 50—Separately derived UPS system serving four-wire-plus-ground loads

where

	NEC	CEC	IEC
Conductor 7	equipment grounding conductor(EGC)	bonding conductor	protective earth conductor
Conductor 8	ground electrode conductor(GEC)	ground conductor	earthing electrode conductor
Conductor 9	ground electrode	ground electrode	earth electrode

9.5 Non separately derived transformerless ups system

Static UPS units are available with and without an integral output isolation transformer. The more recent commercial UPS designs are without any input and output transformers. A typical transformerless UPS topology is shown in [Figure 52](#). Transformerless UPS units do not provide electrical (galvanic) isolation between the UPS ac output and its ac input. As such, transformerless UPS units should not be treated as a separately derived system. Any ground-fault current on the output of the transformerless UPS returns to the source of the ac input and not the UPS inverter output. Transformerless UPS units with 4-wire ac output should be used with a 4-wire ac bypass input to properly reference the transformerless UPS system.

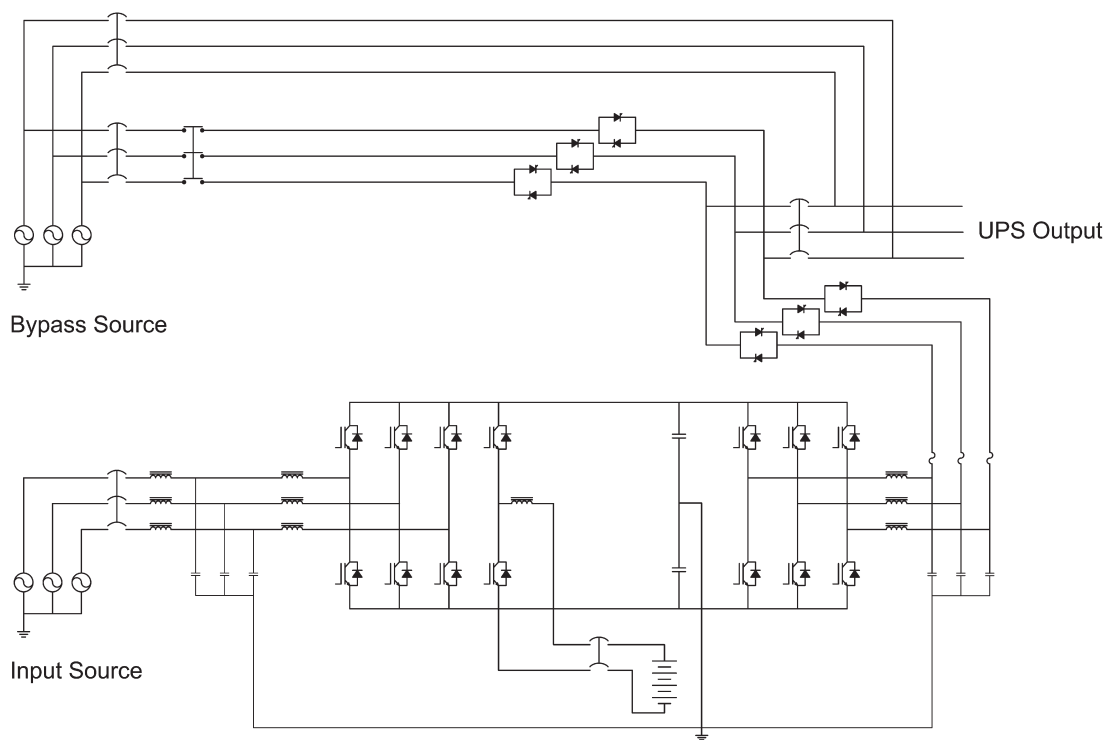


Figure 51—Non separately derived transformerless UPS system

10. Creation of stray currents and potentials

If a current-carrying conductor, even though nominally at ground potential, is connected to earth at more than one location, part of the load current will flow through the earth because it is then in parallel with the grounded conductor. Since there is impedance in both the conductor and the earth, a voltage drop will occur both along the earth and the conductor. With the majority of grounding electrode resistance focused on the area immediately surrounding the electrode, most of the voltage drop in the earth will occur near the point of connection to earth. Because of this nonlinear voltage drop in the earth, most of the earth will be at a different potential than the grounded conductor due to the load current flowing from this conductor to earth.

A protective conductor connected to the same electrode as the grounded load conductor will have a potential difference from most of the earth due to the potential drop caused by the load current. In most instances, the potential difference will be too low to present a shock hazard to persons or affect operation of conventional electrical load equipment. However, minimal potentials have been of sufficient level to be detected by livestock, either by coming in contact with non-current carrying enclosures to which a protective conductor is connected, or where sufficient difference in potential exists between the earth contacts of the different hoofs. Although potential levels may not be life threatening to the livestock, as little as 0.5 V rms can affect milk production [B13].

If a separate protective conductor is run to each building and grounded, then any installed grounded circuit conductor should not be connected to the protective conductor or to the grounding electrode(s). Since no load current would be flowing into these grounding electrodes, the protective conductor should be at earth potential.

Another possible source of multigrounding of a neutral is the use of the neutral for grounding of the frames of cooking ranges or clothes dryers which was once a common practice. If the appliance frame also has a separate connection to earth, multigrounding of the neutral will be achieved. This practice should be avoided in the vicinity of the barns and even at other locations on farms.

At utility service drops, the neutral is grounded at the supply transformer and again at the service entrance. Since the protective conductor has its origin at the service entrance ground, it will have a potential to earth as a function of the voltage drop created by load current in the earth in parallel with the service drop neutral current. For properly installed installations, the magnitude of this potential will be affected by the size and length of the service drop neutral, the magnitude of the neutral current, and the resistance to earth of the service entrance grounding electrode as well as other connections to earth of the protective conductor. Where the bond between the utility neutral and the customer panel is errantly omitted, earth becomes the only neutral current path resulting in abnormally high earth potentials.

There is a remaining source of circulating current when the utility distribution circuit includes a multigrounded neutral. The grounding of the supply-transformer secondary neutral has often been made common with the grounding of the primary neutral. There may be a potential difference between this primary neutral and earth and that there may be primary load current flowing through the ground has been established (see Stetson, Bodman, and Shull [B36]; Surbrook and Reese [B37]; Prothero, DeNardo, and Lukecart [B33]; and Dick [B13]). This will be affected by the neutral current, the location on the distribution feeder, and the effectiveness of the various grounding electrodes.

Neutral-to-ground voltages imposed into the user system from the utility primary neutral cannot be eliminated by system grounding techniques on the premises, although some reduction may be achieved if the service entrance ground is made extremely effective and is located at some distance from livestock facilities. There are active systems to counteract equipment-to-ground voltages produced by utility injections (see Dick [B13]). Also, used are so-called equipotential ground planes, which bring earth surface voltages to the same value as that of equipment, as noted by Dick [B13].

11. Resonantly produced voltages

This term is applied to the voltage that will appear at the junction between reactance of opposite sign connected in series even though the reactance may not actually be resonant at the supply frequency. The variance of the voltage with respect to the supply voltage will be a function of how close the elements are to resonance and the ratio (Q) of inductive reactance to the resistance.

A common instance is the use of series capacitors on low power factor loads where random switching or other variations create objectionable voltage excursions. Figure 52 represents the circuit of a spot welder whose inductance is fixed by the dimensions of the machine but whose resistive load can be varied. With full power factor correction, the voltage rise across the capacitor will be 1.732E at 0.5 power factor and 4.9E at 0.2 power factor. With the ground fault as shown, this 4.9E across the capacitor will be impressed between the source transformer and ground. Both the transformer and its grounding impedance will be subjected to overvoltage. For this reason, such series capacitors should be used only on effectively grounded systems, which will limit the voltage rise to safe values. E is defined as the line-to-neutral voltage.

A more commonly observed series reactance circuit is created when a capacitive load is connected, usually for power factor and/or voltage correction. Since these capacitors are in series with the source reactance of the power system, the voltage is caused to rise. The voltage rise caused by the normal size of power factor capacitors would not be expected to exceed 5% to 10% under the worst conditions, since the system is not approaching resonance at the fundamental power frequency. This is not a different voltage class and does not present a hazard. Discussion here is only to present a familiar example of reactance in series.

Resonance can be achieved, at multiples of the power system frequency, by the addition of power factor capacitors. When there are sources of harmonics, such as nonlinear loads, the resulting harmonic voltages can be raised by a resonant condition. Such voltages would not normally reach hazardous values. A hazardous level, should it occur, would be rapidly reduced by overcurrents in the capacitors causing failures or fuse operations, thus detuning the circuit.

Impulse voltages can be amplified and extended as damped oscillations (ringing) by resonant circuits. These voltages can exceed insulation capabilities.

Resonant conditions prone to continuous oscillation due to lack of resistive loading (damping) can be triggered by switching or by system failures. The most common example is that created by single-phase switching of transformer primaries when there is no secondary load. This produces the ferroresonant condition where the excitation impedance of the transformer interacts with the capacitance of the primary cable.

These resonantly produced voltages are not considered useful system voltages, with the exception of the resistance welder application. Thus, they do not create multi-voltage systems, but are discussed here so that they might be avoided. With the exception of increasing the impulse capability of the insulation, the main defense against these voltages is suppression.

There are other situations where high voltages can be produced by inadvertently created resonant conditions. These are usually the result of insulation failures, equipment failures, or unintended circuit configurations. The voltages are more extreme if conditions at or close to resonance are achieved. When the inductive element has an iron core, the inductance can vary when the iron is saturated due to the high voltage, which at the same time causes nonsinusoidal current with resulting harmonics. This can result in arriving at a resonant condition referred to as ferroresonance. These are not system voltages as have been discussed in the preceding paragraphs, since they are unintended and may be transitory in nature.

In some cases, occurrence of these voltages can be affected or eliminated by the grounding design, but such changes in voltage also may involve choice of transformer design or performance of switching devices. A common cause of ferroresonance is the impressing of voltage across a transformer winding and a conductor capacitance to ground, the conductor having been disconnected from its normal source. If the transformer is wye connected, grounding of the neutral will usually prevent voltage being impressed across this series connection. A resonant condition produced by a grounded coil acting in series with the line-to-ground capacitance of an ungrounded system can be alleviated if the capacitance is shunted by grounding the system.

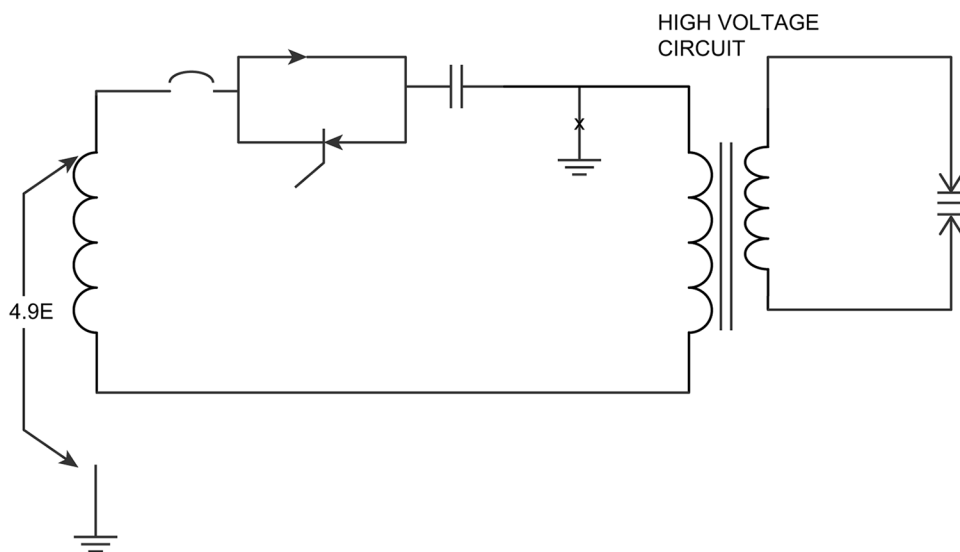


Figure 52—Series capacitor welder

Annex A

(informative)

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